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The Zoom city: working from home, urban productivity and land use

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Abstract

This article investigates the impact of working from home (WFH) on the emergence and structure of monocentric cities. In the long run, WFH raises urban productivity only in sufficiently large cities. Business land rents fall while residential land rents decrease near the business district. Workers have incentives to adopt inefficiently high WFH schemes. In the short run, WFH yields mixed benefits for commuters and firms, which corroborates the low WFH adoption before the pandemic. Advances in digital technology increase the welfare benefits of WFH. Calibration exercises on European capital cities shed light on the quantitative impact of WFH.

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1. Introduction

COVID-19 has affected the labor and land markets in multiple ways. It has forced many companies to adopt more flexible work routines and facilitated the transition to remote work. Working from home (WFH) has become a new reality for a lot of employees—mainly office workers—who are highly educated and specialize in business services. The transition to remote work has also created pressure for changes in land use. It has decreased the demand for office space and increased the demand for home office space. The spatial implications of this transition are, though, unclear. Amid the growing literature on the implications of WFH, this article studies how remote work affects the internal structure and the size of cities, the land and labor markets, and the welfare of their residents.

Will WFH persist in the post-COVID era? Recent studies show that both employers and employees embrace the flexibility of WFH and are willing to adopt new remote work routines that allow employees to work from home multiple days a week.[1] This hybrid

1 See, for instance, Alipour et al. (2023), Bartik et al. (2020), Barrero et al. (2021a, 2021b, 2021c), Brynjolfsson et al. (2020, 2022), Dingel and Neiman (2020) and OECD (2021).

working scheme, which combines remote and on-site work, affects the distribution of economic agents in the interior of cities in multiple ways. Less office work and commuting decrease the willingness of (remote) workers to locate close to their job. According to estate agents, people are reassessing their housing needs, which has increased the demand for larger houses or apartments on the outskirts of many big cities. At the same time, firms vacate some of their buildings because of reduced space needs.

In this article, we use a simple urban economics model of land use where workers and firms compete for space. Firms exchange information and knowledge and benefit from interactions with other firms. As such economies of agglomeration increase their productivity, they have incentives to locate close to each other and form a business cluster.[2] In the absence of remote work, workers want to locate close to their workplace and avoid paying high commuting costs. The formation of large business clusters leads to higher land rents in the areas around them, prevents workers from locating close to their job location, and increases average commuting distances. The balance between economies of business density, commuting cost and land scarcity determines workers' and firms' location decisions.

How do cities change when people can work remotely? WFH changes workers' willingness to pay for high rents around business centers. Peri-urban places where rents are lower become more attractive when workers commute less. At the same time, WFH prevents face-to-face communication between workers not only within each firm but also between firms, which hampers innovation and productivity within the city.[3] WFH, therefore, rebalances not only commuting patterns and land rents but also firm productivity.

To investigate this effect, we distinguish between tasks that require physical presence at the office and tasks that can be (partly) performed from home. In both cases, production externalities in the form of exchange of information and spillovers are important.[4] In this setting, the main difference is that WFH has a direct impact only on the business interactions between employees who partly work from home performing teleworkable tasks.

The aim of this article is to study how WFH affects the spatial interdependence of firms and workers and how it impacts the land and labor markets, as well as welfare. We study how WFH affects the productivity of workers by considering different scenarios for the fraction of work done on-site and remotely. We investigate the differences between the equilibrium and the optimal WFH level and discuss long- versus short-run changes in hybrid working schemes. Our analysis contributes to the discussion that highlights the dangers of too much WFH and considers aspects of the disagreement between workers and

2 The economies of density (Combes and Gobillon, 2015) is the main agglomeration factor explaining the existence of cities (e.g., Fujita and Ogawa, 1982; Lucas and Rossi-Hansberg, 2002). Firms locating within the same urban area benefit from stronger knowledge spillovers (Glaeser et al., 1992), higher innovation and productivity (Jaffe et al., 1993) and reduced cost of moving ideas, goods and labor (Ellison et al., 2010). Baum-Snow et al. (2021) suggest that spillovers are generated by knowledge transfers between workers. See also Moretti (2004) and Greenstone et al. (2010).

3 Atkin et al. (2021) estimate that the transition of one quarter of the Silicon Valley office workers to WFH results in a fall of 17% in face-to-face communication between employees from different firms and lowers the patent citation by 5%. In the same vein, Charlot and Duranton (2006) highlight stronger face-to-face interactions external to firms in more central urban locations and in bigger cities. They further suggest that remote work does not supplement the face-to-face interactions that are external to the firms.

4 We follow the report of the European Commission (2020), where the authors analyze jointly the extent of teleworkability and that of social interactions and find that 65% of the jobs are non-teleworkable because they require a significant amount of social interaction, while the rest 35% are teleworkable, but only 22% of them require social interaction. In this article, we focus on the 87% of the jobs that require some social interaction.

firms. For the sake of conciseness, we focus on spatial equilibria where monocentric city structures emerge. We are not aware of any paper providing any formal theoretical modeling on how WFH will affect cities of different sizes while accounting for interaction externalities—which is the driving force of city formation—and thus, we aim to cover this gap in the literature.

Our results show that WFH facilitates the emergence of monocentric cities and sustains them for a wider range of population sizes. When the city is large, WFH can be beneficial for productivity. On the contrary, in small cities, WFH leads to productivity losses. Business rents fall when workers partly work remotely, while residential rents decrease close to the business district. When WFH results in the expansion of the city, residential rents increase close to the city edges. Welfare benefits associated with remote work occur only in large cities. We also find that the first best WFH intensity is smaller than the one chosen by urban workers. We further show that switching to remote work in the short run (i.e., at fixed prices and city structure) implies higher benefits for long-distance commuters, lower benefits for short-distance ones, and mixed benefits for firms. Besides, we find that advances in digital technology ease the transition to remote work and increase welfare. Finally, we extend the model to more realistic features and perform a calibration exercise on the average and the largest European capital cities. We confirm that workers in larger cities benefit more from WFH.

Recent theoretical contributions study the impact of WFH on different aspects of the urban environment. In particular, Behrens et al. (2021) build a general equilibrium model with three production factors and three sectors. Unlike our article, there is no land competition between firms and residents, and their agglomeration force stems from the product diversity in the urban intermediate sector. Our model reproduces a similar relationship between aggregate productivity and WFH through the channel of business interactions. Our results confirm their findings that WFH is a mixed blessing. Our analysis can also be compared to Brueckner et al. (2022), who briefly discuss the impact of WFH on the internal structure of cities while focusing more on its impact across cities. In their theoretical model, individuals work only from home, while they can live and work in different cities.[5] In our article, we explicitly study the firms' incentive to change their location and the structure of wages and land rents, while Brueckner et al. (2022) do not consider changes in firms' locations.

In a similar context, Gokan et al. (2022) study the residential location decisions of skilled and unskilled workers (i) in a monocentric city and (ii) in a model of two cities that have different productivities. The focus of their paper is on the residential location decisions, as firms locate in the dimensionless central business district (CBD). WFH allows skilled people to work in the more productive city and locate in the cheaper, less productive one. Finally, our article is close to Delventhal et al. (2021) and Delventhal and Parkhomenko (2022) who use a quantitative urban economics model to study the changes in the shape of cities after a permanent increase in the fraction of WFH. Our results confirm their findings with respect to the city structure and the rents for housing and office space. Our simple model though—which is based on the workhorse model of Fujita and Owaga (1982)—allows us to analytically discuss the existence of monocentric city spatial equilibrium, the optimal city structure, the optimal fraction of remote work, as well as to

5 Brueckner and Sayantani (2023) generalize this model by adding a group of non-remote workers and show that the main conclusions of Brueckner et al. (2022) remain unaffected.

point out the differences between the short- and the long-run equilibria. It also helps us discuss aspects of disagreement between workers and firms and explain the low prevalence of WFH before the pandemic.

This article is also related to a number of recent empirical studies. In this context, Liu and Su (2021) study the impact of COVID-19 on the housing demand in the USA and show that there is a higher drop in housing demand in neighborhoods with higher home values. Brueckner et al. (2022) also show that WFH decreases house prices and rents in high-productivity counties, while Gupta et al. (2022) show that the shift to remote work decreased house prices and rents in city centers and increased them in areas farther away from the center.[6] Urban areas have been particularly affected by the changes related to the switch to remote work, with the highest remote work levels being observed in more densely populated cities in the USA, which are specialized in high-skill jobs (Althoff et al., 2022).[7] The shift to remote work has also inevitably affected workers' productivity and urban production. There is no consensus, though, about the direction of this effect. A number of studies find an increase in the productivity of remotely working employees, while other studies find a negative effect. The majority of those studies focus on within-firm productivity interactions.[8]

The remainder of the article is organized as follows. Section 2 presents the model, while Section 3 discusses the spatial equilibrium of the monocentric city. Section 4 discusses the equilibrium rents and wages. Section 5 is devoted to the welfare analysis and highlights the difference between the optimal and the equilibrium WFH levels. Section 6 discusses the implementation of WFH in the short run and also shows how the significant advances in digital technology affect the productivity of remote workers and the implementation of remote work. In Section 7, we calibrate our model, and Section 8 concludes the article.

2. Model

We consider a linear city model with homogeneous firms, homogeneous residents-workers and absentee landlords. The city expands on the unit-width segment where firms and workers interact through competitive labor and land markets. There are two forces that promote the formation of business and residential areas: business production externalities and workers' commuting cost. Firms tend to locate closer to each other because geographical proximity increases their productivity. Following the literature (e.g., Fujita and Ogawa, 1982; Lucas and Rossi-Hansberg, 2002), we consider agglomeration benefits through face-to-face communication and exchange of information among firms. As it is commonly assumed in urban economics models, workers face a trade-off: locating closer

6 The decreasing rents in high-density areas and CBDs of America's largest cities have also been confirmed by other recent studies (e.g., Lennox, 2020; Ramani and Bloom, 2021).

7 Also, De Fraja et al. (2021) show that the share of spending in retail activity in large business centers has decreased more than in more residential areas.

8 An earlier study by Bloom et al. (2015) found a 13% increase in the productivity of remotely working employees at the call center of a Chinese travel agency, while Davis et al. (2021) show that the development and the adoption of technological innovations that facilitated remote working during the pandemic have boosted WFH productivity by 46%. On the other hand, using data from over 10,000 skilled professionals working at a large Asian IT services company, Gibbs et al. (2023) found that the average effect of working from home on productivity was negative. Similarly, Shen (2022) found that the state-imposed workplace closures during the COVID-19 pandemic decreased the output of individuals working in tech by 0.5%.

to firms relaxes their commuting costs but increases their land rents. In the absence of remote work, the balance between those forces determines the land use. WFH adds several features to the model: on the one hand, workers save commuting cost but must dedicate space at home as a work area. On the other hand, firms save office space, but remote work prevents face-to-face communication with their business neighbors. Below, we study how these additional features affect the equilibrium urban structure in a monocentric city model.

We consider a closed city with an exogenous mass N of workers who reside in the city and an endogenous mass M of firms that produce there. Workers reside at locations denoted by $x \in \mathbb{R}$ and firms produce at locations denoted by $y \in \mathbb{R}$. Firms and workers compete for the same land in the city. The densities of residents and firms are denoted by $n(x)$ and $m(y)$ and satisfy $\int n(x)\mathrm{d}x = N$ and $\int m(y)\mathrm{d}y = M$. Workers consume an (inelastic) unit of land and a quantity c of a composite good, available in the national market at a price normalized to one.[9] They derive linear utility from the consumption of the composite good, $U(c) = c$. WFH allows workers to spend a share β_t of their time at the office and a share $1 - \beta_t$ to work remotely from home. A worker residing at x and working at y gets a salary $w(y)$ and incurs a commuting cost given by $\beta_t t|x - y|$, where t is the cost per unit of distance. For simplicity, we assume that each worker uses one unit of space for residential purposes and γ units as a home office space. The total use of space per resident is therefore $1 + \gamma$, and the total amount of space used for residential purposes in the interior of the city is $(1 + \gamma)N$. The budget constraint of a worker living at x is given by

$$c(x) + (1 + \gamma)R(x) + \beta_t t|x - y| \leq w(y), \tag{1}$$

where $R(x)$ is the land rent.

Firms are assumed to have equal sizes and to produce a composite good that is shipped and sold at a unit price in the national market. Each firm locating at y uses a unit mass of workers and pays $w(y)$.[10] As a result, labor market clearing imposes that $N = M$. The size of office space depends on the fraction of remote work. For the sake of simplicity, we assume that each firm uses one unit of land when workers work full-time on site. When workers are allowed to work from home and spend a share β_t of their time at the office, firms adjust their office needs accordingly and use $\beta_s < 1$ units of office space. The total use of office land is then $\beta_s M$, while the total amount of space used both for residential and office purposes is $(1 + \gamma + \beta_s)M$ units of land. The firm's profit is given by

$$\pi(y) = A(y) - \beta_s R(y) - w(y), \tag{2}$$

where $R(y)$ and $w(y)$ denote the land rent and labor costs, respectively. In this expression, $A(y)$ denotes the production of the firm which is discussed below.

The focus of this article is to discuss the impact of WFH in the presence of economies of business density, which are related to employee spillovers. We thus assume that there

9 For simplicity, we assume that the consumption of land is equal to one. Fixed land consumption by both households and firms is assumed in Fujita and Thisse (2002, Chapter 6.3), Regnier and Legras (2018) and Kyriakopoulou and Picard (2021).

10 The firms' land and labor demands are extended to different scalars in the calibration exercise (see Section 7 and Appendix C).

are tasks that are performed on site, and other tasks that can be performed both on site and remotely. This division of tasks is in line with Adams-Prassl et al. (2022) who use survey data from the USA and the UK to predict the share of tasks that can be done from home for different occupation-industry pairs. For example, in 'Office and Administrative Support' occupations, the share of tasks that can be done from home ranges from less than 30% in 'Human Health and Social Work' industry to about 75% in 'Information and Communication' industry. In 'Sales and Related Occupations', the corresponding share ranges from less than 10% in 'Wholesale and Retail Trade' to about 90% in 'Financial and Insurance Activities'. According to Sostero et al. (2020), these occupations require a significant amount of social interactions.

Given this division of tasks, we assume that a firm's production is the outcome of the interaction between its own agents and the agents of other firms. Each interaction contributes to the production of α goods (or services) and incurs a cost $\tau|z-y|$, where τ measures the interaction cost per unit of distance, and $|z-y|$ is the distance between the two firms. This interaction yields $(\alpha-\tau|z-y|)$ units of goods. The frequency of the interactions for tasks that can be performed only on-site is denoted by ϕ, while the frequency of the interactions for the rest of the tasks in the absence of WFH is normalized to one. Hence, in the absence of WFH, the firm produces $(1+\phi)\int(\alpha-\tau|z-y|)m(z)\mathrm{d}z$ units of goods where $m(z)$ is the density of firms at location z.[11] As a result, the productivity of the firm rises with a higher density of firms in nearby areas, which reflects economies of business density.[12] For simplicity, we focus on the case of 'global interactions' where every interaction yields a positive benefit: $\alpha-\tau|z-y|>0$. This sets an upper bound on the distance between businesses and therefore on the city size.[13]

In this article, we consider that when working remotely, the frequency of interactions among employees declines. To make things simple, we assume that an employee's probability to have an activity with another employee outside her firm is given by $\beta_a^{1/2}$, which is a concave increasing function of her on-site presence. The probability is one ($\beta_a=1$) when the employee is full time on-site and decreases more and more rapidly when she works more often from home, which reflects decreasing returns in employees' interactions. Assuming independent and identical probabilities for all employees, a successful match between two employees who work a fraction of their time at the office is given by the probability $\beta_a^{1/2}*\beta_a^{1/2}=\beta_a$.[14] If their work location is at y and z, then they produce $\beta_a(\alpha-\tau|z-y|)$ units of goods. If all interactions are taken into account, the production function in the presence of WFH becomes

$$A(y)=(\beta_a+\phi)\int(\alpha-\tau|z-y|)m(z)\mathrm{d}z. \qquad (3)$$

The production function (3) captures the benefit of business proximity in a linear way. Although this is a strong simplification of actual production schemes, its exact shape is

11 For a discussion on how the spatial concentration of firms affects productivity, see Rosenthal and Strange (2020).

12 Empirical research in urban and regional economics provides ample evidence of such type of agglomeration forces (see e.g., Ciccone and Hall, 1996; Rosenthal and Strange, 2008).

13 For analysis of 'local interactions', see Augeraud et al. (2021).

14 β_a replaces 1 in the term $(1+\phi)$ in the previous paragraph.

not reported by the empirical literature and cannot be used as guidance. As in Fujita and Ogawa (1982) and subsequent studies, the linear structure with respect to location y drastically helps the analytical discussion of city structure below. The linear structure with respect to the intensity of professional interactions for non-teleworkable (ϕ) and teleworkable tasks (β_a) is novel and helps to disentangle the economies of density that are linked to the activities with potential for remote work and those without.[15]

To sum up, in this model, WFH is driven by four parameters: β_t (the fraction of on-site work/commuting frequency), β_s (office space when employees work from home a share $1-\beta_t$ of their time), β_a (strength of employee spillovers when people work from home a share $1-\beta_t$ of their time), and γ (home office space when people work from home). All these features may move in different proportions and in non-linear ways. In this article, we allow these parameters to respond differently in various fractions of WFH. However, we assume that β_t, β_s, and β_a move in the same direction, meaning that lower office presence (β_t) decreases the probability of interaction (β_a) and also, decreases the needs for office space (β_s) per employed worker. We investigate the impact of each one of those parameters both in the theoretical model below and in the calibration exercise that follows. Note that no WFH implies $\beta_t = \beta_s = \beta_a = 1$ and $\gamma = 0$.

Residents and firms individually choose their location in the city. In theory, they may locate in the same area or in different districts. In this article, we focus on spatial equilibria sustaining monocentric cities.

3. Monocentric city spatial equilibrium

A monocentric city includes a CBD on the interval $[-b_1, b_1]$ that is surrounded by two symmetric residential areas of equal size on the intervals $[-b_2, -b_1)$ and $(b_1, b_2]$, with $0 < b_1 < b_2$. In the presence of WFH, each firm and resident, respectively, use β_s and $1+\gamma$ units of land so that the total size of the business area is equal to $\beta_s M$ and the total size of the residential areas to $(1+\gamma)M$. Because of symmetry, we can restrict our attention to the RHS of the city, that is, $x, y \in [0, b_2]$. The district border between firms and residents is given by $b_1 = \beta_s M/2$ while the city border is given by $b_2 = (1+\gamma+\beta_s)M/2$. The length of residential area is thus equal to $b_2 - b_1 = (1+\gamma)M/2$. The firm density in the CBD is $m(y) = 1/\beta_s$ while the residential density is $n(x) = 1/(1+\gamma)$. Maintaining global interactions in the CBD implies that $\alpha/\tau > 2b_1 = \beta_s M$.[16] This restricts our study to cities with sizes smaller than $\overline{M} \equiv \alpha/(\tau\beta_s)$,

15 Our analysis focuses on between-firm spillovers. The model can readily encompass the presence of within-firm spillovers by adding a linear term in the production function (3) so as $A(y) = \theta(\beta_a + \phi)\int(\alpha - \tau|z-y|)m(z)dz + (1-\theta)(\beta_a+\phi)\alpha$, where θ and $(1-\theta)$ refer to the shares of between- and within-firm spillovers, respectively. Using $M = \int m(z)dz$, the production function becomes $A(y) = (\beta_a+\phi)\int(\hat{\alpha} - \hat{\tau}|z-y|)m(z)dz$, where $\hat{\alpha} = \alpha[\theta + (1-\theta)/M]$ and $\hat{\tau} = \theta\tau$ which are exogenous in our closed city model. The parameters α and τ can therefore be interpreted as a combination of between- and within-firm interactions.

16 Under global interactions, $\alpha - \tau|y-z| > 0$ for any $\{y, x\} \in [-b_1, b_1]$.

which we assume in the following. The analytical solutions of this section can be found in Appendix A.

3.1. Urban production

In a monocentric city where employees are partly allowed to work from home, the firm's production function is given by Equation (3) with business density $m(z) = 1/\beta_s$ and district border $b_1 = \beta_s M/2$. We can thus write the productivity as

$$A(y) = \begin{cases} (\beta_a + \phi)\left[M\alpha - \tau\left(\frac{1}{4}\beta_s M^2 + y^2/\beta_s\right)\right] & \text{if} \quad y \in [0, \beta_s M/2] \\ (\beta_a + \phi)M(\alpha - y\tau) & \text{if} \quad y \in [\beta_s M/2, (1+\gamma+\beta_s)M/2] \end{cases}. \tag{4}$$

Production is a concave and quadratic function of y in the CBD and linearly decreasing function of y in the residential area.

Within the business district, more intense WFH ($d\beta_a, d\beta_s < 0$) decreases firm productivity if and only if $dA(y) = \left(\partial A(y)/\partial\beta_a\right)d\beta_a + \left(\partial A(y)/\partial\beta_s\right)d\beta_s < 0$. It can be shown that higher fractions of WFH induce two opposing effects. On the one hand, less time spent at the office decreases firm's productivity because employees have less face-to-face interaction with employees from other firms ($\partial A(y)/\partial\beta_a > 0$). On the other hand, smaller office space increase productivity ($\partial A(y)/\partial\beta_s < 0$) because the CBD becomes more compact (rise in $m(z)$ and fall in b_1), which in turn, decreases the geographical distance between firms and facilitates the interactions among employees (see Appendix A). The result thus depends on the city characteristics and on the trade-off between lower employee spillovers and office space savings.

This trade-off is also reflected in the total urban production given by $TP = \int_{-b_1}^{b_1} A(y)m(y)dy = (\beta_a + \phi)(\alpha - \beta_s\tau M/3)M^2$, which decreases with lower employee spillovers (β_a) and increases with smaller office space (β_s). Total production decreases under WFH if and only if $TP \le TP^0$ where TP^0 denotes the production in the absence of WFH ($\beta_t = \beta_s = \beta_a = 1$ and $\gamma = 0$). After simplification, this is equivalent to

$$M \le \frac{3\alpha}{\tau B},$$

where $B = [(1+\phi) - (\phi + \beta_a)\beta_s]/(1-\beta_a) > 0$. As a result, *more intense WFH has a negative impact on total urban production in small cities and a positive one in large cities.* Similarly, *WFH decreases the firm productivity $A(b_1)$ at the CBD edge if the city size is small enough*:

$$M \le \frac{2\alpha}{\tau B}.$$

We summarize this result in the following proposition:

Proposition 1. *Increasing fractions of WFH have a negative impact on total urban production in small cities and a positive one in large cities.*

Also, it can be shown that, for a linear relationship between the WFH parameters (i.e., constant $d\beta_s/d\beta_a$), total urban production is given by $(\beta_a + \phi)[\alpha - \beta_a \tau M(d\beta_s/d\beta_a)/3]M^2$, which is a concave function of the parameter β_a and reaches a maximum when $\beta_a = \beta_a^{TP} = 3\alpha(d\beta_s/d\beta_a)/(2\tau M) - \phi/2$. Hence, *WFH induces a non-monotonic relationship of total urban productivity with respect to the WFH parameters*. When β_a^{TP} lies between 0 and 1 and as employee spillovers β_a decrease from 1 to 0, total production first increases, then reaches a maximum level at β_a^{TP}, and finally decreases. In this sequence, the benefits from a more dense and compact business district first outweigh the losses from lower employee spillovers, then equate them, and finally are dominated by them. The same is true for the average urban productivity, *TP/M*. This holds for 'well-behaved' non-linear relationships between the WFH parameters provided that the above total urban production function remains bell-shaped. This property compares to Behrens et al.'s (2021) discussion of the 'mixed blessing of WFH' whereby the economy benefits from WFH only when it remains mild. While these authors base this property on the existence of product diversity in an urban intermediate sector, the present model generates it from the existence of economies of business spillovers and business district compactness.

3.2. Spatial equilibrium

In a spatial equilibrium, land is assigned to its highest value. Since workers are able to relocate at no cost within the city, they must reach the same utility level U^*, independently of their workplaces and residences (Fujita and Thisse, 2002). If it were not the case, they would have incentives to move to the urban location that offers the highest utility. The maximum land rent that they can offer in order to locate at a location x is given by the following residential bid-rent function:

$$\Psi(x, U^*) = \max_y \frac{w(y) - \beta_t t|x - y| - U^*}{1 + \gamma}. \tag{5}$$

In the business sector, the free entry assumption ensures profits are equal to zero: $\pi(y) = 0$. Therefore, the maximum land rent that a firm can offer is given by the following business bid-rent function:

$$\Phi(y) = \frac{A(y) - w(y)}{\beta_s}. \tag{6}$$

In equilibrium, land is allocated to the agent that offers the highest bid-rent. In particular, in the monocentric city, the land rent $R : \mathbb{R}^+ \to \mathbb{R}^+$ must be equal to the firms' bid rent Φ in the business district and to the residents' bid rent Ψ in the residential area. The land market equilibrium then satisfies the following conditions[17]:

$$R(y) = \Phi(y) \quad \text{if } \Phi(y) \geq \max\{\Psi(y, U^*), 0\}, \qquad y \in [0, b_1], \tag{7}$$
$$R(x) = \Psi(x, U^*) \text{ if } \Psi(x, U^*) > \max\{\Phi(x), 0\}, \qquad x \in [b_1, b_2]. \tag{8}$$

17 For simplicity, we approximate the value of alternative use of land (farming) to zero.

3.2.1. Necessary conditions

At the district borders b_1 and b_2, land-rent arbitrage imposes the following necessary equilibrium conditions:

$$\Phi(b_1) = \Psi(b_1) \text{ and} \tag{9}$$
$$\Psi(b_2) = 0. \tag{10}$$

Condition (10) expresses the land-market competition between residents and farmers. Importantly, condition (9) expresses the land-market competition between firms and residents.[18] Furthermore, firms and residents are also active in the labor market.

Solving the utility maximization problem, we obtain the equilibrium utility in the closed city, that is, $U^* = w(y) - \beta_t t(x-y) - (1+\gamma)R(x)$. Taking the working location $y = b_1$ as a reference point, we can define the following labor-commuting arbitrage condition for residents living at x:

$$w(y) + \beta_t ty = w(b_1) + \beta_t tb_1, \quad y \in [0, b_1]. \tag{11}$$

That is, in equilibrium, workers should be compensated with higher wages when they work further away from their residences (smaller y).[19] Otherwise, they would have incentives to work in locations that are closer to their residences. This simplifies the residential and business bid rents as

$$\Psi(x, U^*) = \frac{w(b_1) - \beta_t t(x - b_1) - U^*}{1+\gamma} \text{ and } \Phi(y) = \frac{A(y) - w(b_1) - \beta_t t(b_1 - y)}{\beta_s}. \tag{12}$$

The identities (9) and (10) solve for the equilibrium utility U^* and wage $w(b_1)$ (see Appendix A) that will help characterize the effect of WFH below. Before proceeding with this discussion, it is important to establish the sufficient condition for which the monocentric city is a spatial equilibrium.

3.2.2. Existence

We now check the existence of the spatial equilibrium. As pointed out earlier, firms and residents may locate in the same area rather than in separate districts. To show that conditions (7) and (8) hold, we need to prove that the bid rents do not cross twice on the interval $[0, b_2]$. Indeed, the above analysis shows that the residential bid-rent function Ψ is linear on $[0, b_2]$. Also, as a linear function of the productivity A, the business bid-rent function Φ inherits the properties of A: it has a concave and quadratic piece on $[0, b_1]$ and a linear decreasing piece on $[b_1, b_2]$, is continuous, and has a continuous derivative at b_1. As a consequence, it can readily be shown that the bid rents cross only at one location b_1 on the interval $[0, b_2]$ if and only if $\Phi(0) > \Psi(0)$. Using the above definitions and conditions (see Appendix A), the latter condition holds, and the monocentric city is a spatial equilibrium if and only if

18 This condition is absent in most monocentric city analyses where the CBD is assumed to offer an unlimited amount of land to firms (e.g., Brueckner et al., 2022; Gokan et al., 2022).

19 $w(y) > w(b_1)$ for $|y - x| > |b_1 - x|$. Condition (11) is also obtained from the first-order condition of the bid rent (5) w.r.t. y, which is equal to: $w'(y) + \beta t = 0$. Integrating this expression on the interval $[y, b_1]$ gives Equation (11).

$$N > N_m \equiv \frac{2t}{\tau} \frac{\beta_t}{\beta_a + \phi} \frac{1 + \gamma + \beta_s}{1 + \gamma}. \tag{13}$$

As shown in the literature, monocentric cities are spatial equilibria under low enough commuting cost t and high enough economies of density measured by τ. Otherwise, residents have incentives to locate to the city center, which breaks the monocentric configuration and leads to the formation of a mixed area at the geographical center of the city (see Fujita and Ogawa, 1982). It is apparent that N_m falls with smaller β_t and β_s and larger β_a and γ. The effect of WFH on the existence of a monocentric city equilibrium goes through three channels. First, WFH discourages the emergence of monocentric cities because it reduces business spillovers (lower $\beta_a + \phi$), which reduces economies of business density and therefore firm productivity. This impedes firms to sustain the high land rents in the CBD. Second, WFH encourages the formation of monocentric cities because it reduces commuting costs (lower $t\beta_t$) and entices residents to live away from their work location. At the same time, remote workers need additional home office space and prefer to locate away from the business center where land rents are high (γ reduces the ratio $(1 + \gamma + \beta_s)/(1 + \gamma)$ in the above expression).

Comparing condition (13) to the same condition with no WFH, it can readily be shown that monocentric cities are sustained for a larger range of population sizes if and only if

$$\beta_t(1 + \gamma + \beta_s)(1 + \phi) < 2(\beta_a + \phi)(1 + \gamma). \tag{14}$$

This condition holds if WFH has a larger impact on on-site presence and office space (β_t and β_s) than on employee spillovers (β_a). More precisely, the condition always holds if $\beta_t \leq \beta_a$, that is, if on-site presence drops faster than employee spillovers. In other words, WFH should not have a large negative impact on the productivity of firms, which is in line with the results of related empirical studies (see Section 2). This analysis is summarized in the following proposition:

Proposition 2. *WFH facilitates the existence of monocentric cities for a wider range of population sizes if and only if (14) holds. This is always the case if* $\beta_a \geq \beta_t$.

We now study the properties of land rents and wages.

4. Equilibrium rents and wages

Given the equilibrium existence conditions, we can now discuss the determinants of the equilibrium prices for land and labor.

4.1. Land and labor-market arbitrage

The monocentric city equilibrium in the land and labor markets can be explained with the help of two figures. Figure 1 describes the arbitrage in land and labor markets. The left panel describes the arbitrage in land and labor markets at the border of the business district, $x = b_1$. As expressed in Equation (12), the equilibrium is determined by the land rent and wage paid and received by firms and residents at b_1. The decreasing schedule in the same panel represents the firms' arbitrage between wage and land rent. Given that free entry imposes zero profits, firms must pay a lower land rent if wages rise. As shown in Equation (12), they pay the production value $A(b_1)$ to workers if land rent is nil. By

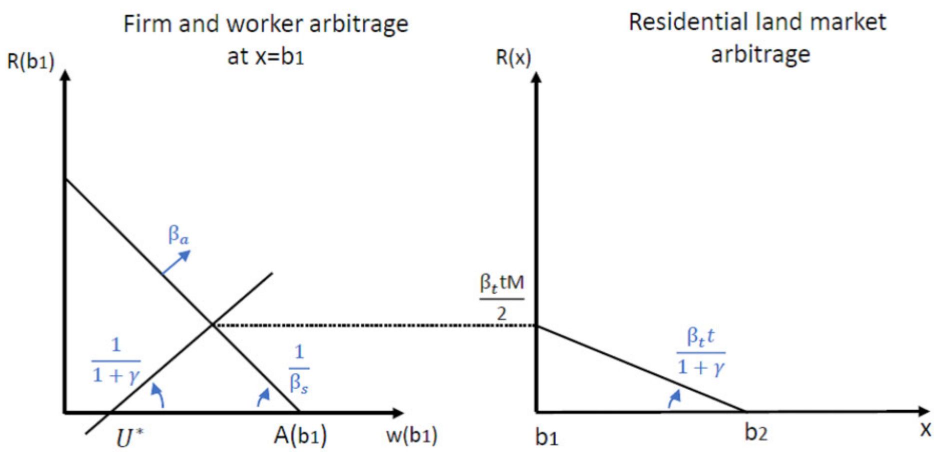


Figure 1. Land and labor-market arbitrage in monocentric city equilibrium.

contrast, if wages are nil, they pay the production value for each unit of land to landlords, that is, $A(b_1)/\beta_s$. The slope of this curve is given by $1/\beta_s$.

The increasing schedule, in the left panel of Figure 1, reflects the arbitrage for residents locating at b_1. Because they are indifferent to work in any firm, we can consider residents who live and work close to the location $y = b_1$ and therefore have almost zero commuting costs. For a given utility, larger wages allow them to pay a higher land rent (see Equation (12)). The slope of the curve is given by $1/(1+\gamma)$. If the land rent is nil, they accept working and living there for a wage equal to $w(b_1) = U^*$. So, the horizontal axis also reads as the equilibrium utility. In arbitrage, a higher productivity $A(b_1)$ raises wages and rents while a higher utility U^* raises wages and reduces land rents, which is reminiscent of Roback's (1982) analysis.

The right panel describes the land-market arbitrage at the city edge, as expressed in Equation (10). It displays the land rent in the residential district, starting from the business district border b_1. As shown in Equation (12), residential land rents fall at the rate $-\beta_t t/(1+\gamma)$ as residents move away from the city center and become zero at the city edge $x = b_2$. At the border between business and residential districts ($x = b_1$), the land rent is equal to $\beta_t tM/2$. The monocentric city spatial equilibrium is defined by the land- and labor-market arbitrage conditions. Thus, the residential land rent at $x = b_1$ in the right panel must be equal to the business land rent at the same location in the left panel. This determines the equilibrium wage level that then yields the equilibrium utility, as shown in the horizontal axis.

WFH has an impact on all the curves of Figure 1. Indeed, increasing fractions of WFH imply lower on-site presence β_t and larger home office space γ. Figure 2 depicts the effect of WFH as the parameters change from (β_t, γ) to (β_t', γ') with $\beta_t' < \beta_t$ and $\gamma' > \gamma$ (see blue dashed lines). First, in the right panel, WFH flattens the residential land rent and shifts it to the right because residents demand more space. The land rent paid at $x = b_1$ is equal to $\beta_t' tM/2$ and therefore decreases with WFH. Second, as discussed in Section 3.1, WFH may increase or decrease productivity A according to the city size and WFH intensity. For the sake of exposition, let us concentrate on large cities so that WFH increases $A(b_1)$ so that the firms' arbitrage schedule moves up in the left-hand panel. As a result, the lower (residential) land rent and the higher productivity increase wages. Finally, the

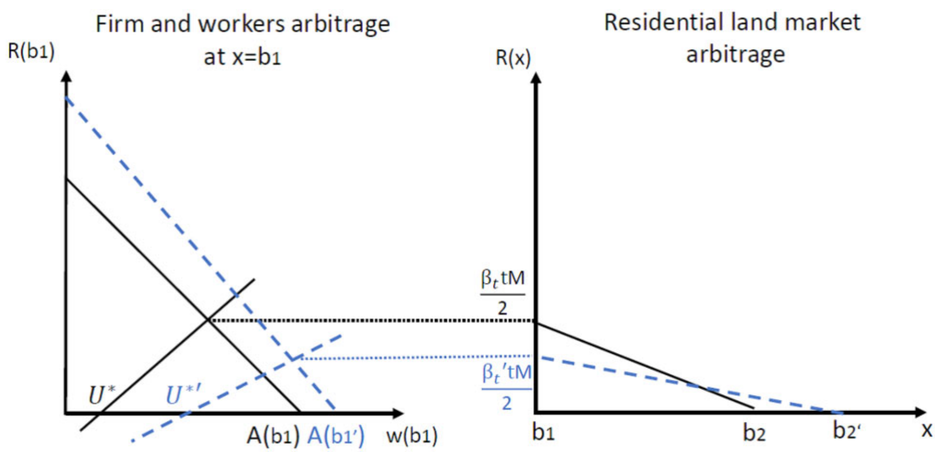


Figure 2. Land and labor-market arbitrage in monocentric city equilibrium.

impact on utility is given by the residents' arbitrage schedule in the left panel, which is pushed to the right. If WFH requires small home office space, its slope $(1/(1+\gamma))$ does not change much, and the utility increases under WFH as shown in Figure 2.

From this discussion, it is easy to highlight cases where WFH yields a lower equilibrium utility. This happens if the productivity A falls, which has been shown to be the case in small enough cities. It also occurs if the home office space is large and flattens the schedule for the residents' arbitrage. Hence, the overall effect of WFH depends on the specific parameters γ, β_t, β_s and β_a and must be analytically determined.

We formalized this discussion in the following subsections.

4.2. Residential land rents

After plugging the equilibrium wage and utility into $\Psi(x, U^*)$, the residential land rent is given by

$$R(x) = \frac{\beta_t t}{1+\gamma}\left[(1+\gamma+\beta_s)\frac{M}{2} - x\right], \tag{15}$$

for $x \in [b_1, b_2]$ (see Appendix A). The land-market arbitrage implies that this land rent is zero at the city border $b_2 = (1+\gamma+\beta_s)M/2$. The residential land rent increases when workers locate closer to the business center (smaller x). More precisely, it is equal to the commuting cost savings that residents get when they locate closer to the center. Residents have the same net salary across firms (see Equation (11)) and differ only in their commuting patterns to the business center. Knowing the residential location, landlords capture those commuting cost savings, which are linear because commuting cost is linear in distance. The linear curves of Figure 3 illustrate this result.[20]

WFH decreases the gradient of residential land rent $t\beta_t/(1+\gamma) < t$, which falls with lower β_t and higher γ. Smaller on-site presence β_t reduces commuting costs while larger home office space γ spreads the commuting cost savings over larger land plots. Brueckner

20 The bell-shaped curves are explained in the next subsection.

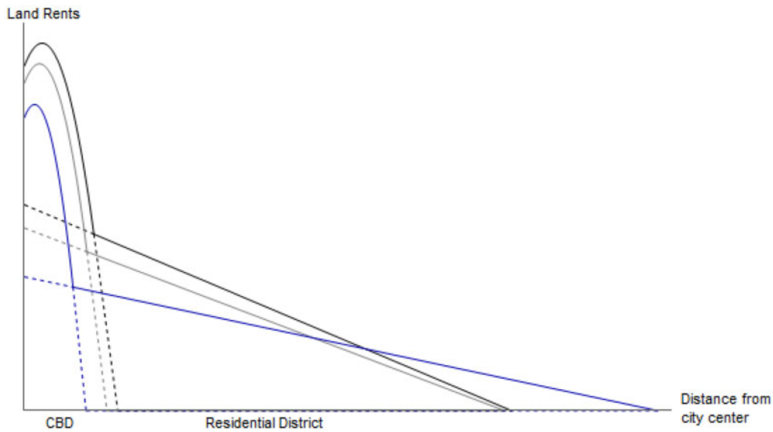


Figure 3. Land rents in the business center and in the residential district.

et al. (2022) empirically show this relationship between land-rent gradient and WFH. Figure 3 illustrates this result. More specifically, the black curve represents the land rents without WFH ($\gamma = 0$, $\beta_t = \beta_s = \beta_a = 1$), the gray curve has $\beta_t = \beta_s = \beta_a = 0.9$ and $\gamma = 0$, and the blue one has $\beta_t = \beta_s = \beta_a = 0.7$ and $\gamma = 0.4$.

From this, it can be deduced that if WFH reduces the city border $b_2 = (1 + \gamma + \beta_s)M/2$ (gray line), it decreases the value of residential land rent everywhere. In this case, the land rent rotates counterclockwise and shifts to the left. This happens if $\gamma < 1 - \beta_s$; that is, if the land used for home office space is smaller than the land savings by firms. Otherwise, if $\gamma > 1 - \beta_s$, the city expands, and the residential district spreads over the farming land, which raises land rent above zero around the city border. So, the land rent may rise in some sections of the residential district and fall in others. To solve this ambiguity, we define $R^0(x) = t(M - x)$ as the land rent in the absence of remote work ($\beta_t = \beta_s = 1$ and $\gamma = 0$). Then, it can be shown that there exists a location $x_a \in (b_1, b_2)$ such $R(x) \geq R^0(x)$ if and only if $x \geq x_a$ (see Appendix A). In this case, WFH reduces the residential land rent on $[b_1, x_a)$ and raises it on $(x_a, b_2]$. On the former interval, land rents fall because landlords are restrained to reap lower savings in commuting cost while they increase in the latter interval because residents demand more space.

The total residential land rent is given by $TR^{\text{res}} = 2\int_{b_1}^{b_2} R(x)\mathrm{d}x = \frac{1}{4}\beta_t t(1 + \gamma)M^2$, which falls with lower β_t, rises with larger γ, and therefore implies an ambiguous effect of WFH. It can be shown that this is smaller than the total rent in the absence of WFH (where $\beta_t = 1$ and $\gamma = 0$) if and only if $\gamma < (1 - \beta_t)/\beta_t$. WFH hence reduces total residential land rent if the land used for extra home office space is not too large compared to the fraction of remote work, which concurs with our discussion above. The average residential land rent is given by $AR^{\text{res}} = TR^{\text{res}}/(2(b_2 - b_1)) = TR^{\text{res}}/((1 + \gamma)M) = \frac{1}{4}\beta_t tM$, which increases in β_t. As a consequence, *WFH reduces the average residential land rent*. This analysis is summarized in the following proposition:

Proposition 3. *WFH decreases the residential land rent everywhere if* $\gamma < 1 - \beta_s$. *Otherwise, it decreases it near the city center and increases it near the city edges. Higher fractions of remote work reduce the average and the total residential land rents.*

Finally, we turn to the impact of WFH on house prices. Under WFH, residents use more space and pay the house price, that is here defined as $(1+\gamma)R(x)$. WFH raises house prices if and only if $(1+\gamma)R(x) > R^0(x)$ where the RHS is the house price in the absence of remote work. It can be shown that there exists a location x_b such that WFH decreases house prices on $[b_1, x_b)$ and increases them on $(x_b, b_2]$ (see Appendix A). Since the location x_b is not the same as x_a, WFH may induce opposite changes in land rents and house prices. In particular, WFH increases land rents but decreases house prices in the interval $[x_a, x_b]$ when $\gamma > 1 - \beta_s$ and leads to the opposite change in the interval $[x_b, x_a]$ otherwise. The average house price is given by $AR * (1+\gamma)$, or equivalently, $\frac{1}{4}\beta_t tM(1+\gamma)$. This increases with larger home office space but decreases with lower on-site work. In particular the average house price increases with WFH if $\beta_t(1+\gamma) > 1$, or equivalently, if $\gamma > (1-\beta_t)/\beta_t$, which is true for large enough home office space. To sum up, house prices and rents decline in more central areas and increase away from the center, which is in line with recent studies showing that the more extensive WFH during the COVID-19 pandemic flattened the price and bid-rent curves in most US metropolitan areas (Brueckner et al. 2022; Gupta et al. 2022). This leads to the following proposition:

Proposition 4. *WFH decreases house prices near the city center and increases them near the city edges. Average house prices rise if and only if* $\gamma > (1-\beta_t)/\beta_t$.

4.3. Business land rent

The business land rent is given by $R(y) = \Phi(y)$ and simplifies to

$$R(y) = (\beta_a + \phi)\tau\left[\left(\frac{M}{2}\right)^2 - \left(\frac{y}{\beta_s}\right)^2\right] + t\frac{\beta_t}{\beta_s}y. \tag{16}$$

for $y \in [0, \beta_s M/2]$ (see Appendix A). The first term is equal to $[A(y) - A(b_1)]/\beta_s$, which means that landlords extract a rent only from the production surplus created at location y in excess of the output at the border of the business district b_1. If they were extracting more, firms would relocate just beyond this border. The second term is a compensation for commuting cost inside the business district, which ensures that the worker will choose firm at location y. Since productivity is concave with respect to distance from the geographic city center, the first term is also concave and contributes to the concavity of the business land rent (see concave curves in Figure 3). Note that stronger business spillovers $(\beta_a + \phi)$ raise this rent as landlords can reap firms' profit from stronger economies of business density.

What is the impact of WFH? It is apparent that the business land rent does not depend on the resident land size, $1+\gamma$. It decreases with lower employee spillovers β_a as the firm's productivity falls. It also decreases with lower commuting frequency β_t as firms can now offer lower compensation to workers for their trips inside the business district. Yet, the impact of smaller office space is ambiguous. It is shown in Appendix A that, ceteris paribus, there exists a location $\tilde{y}$ such that a smaller β_s increases business land rents in the interval $[0, \tilde{y}]$ and decreases in $(\tilde{y}, b_1]$. This is because a smaller β_s increases the land productivity of every firms and because the firms closer to the CBD benefit more from a higher productivity due to their better proximity to other firms. Ultimately, the total impact of WFH on the business land rents will depend on the magnitude of each parameter, β_a, β_t and β_s. However, it is easily shown that WFH reduces the business land rents in every CBD location if $\beta_t \leq \beta_s$. Indeed, under this sufficient condition, the second term in expression (16) falls from ty to the lower value $t(\beta_t/\beta_s)y$ after the transition to WFH, while the first term also decreases in all CBD locations with smaller β_a and β_s. This is true when office space savings $1-\beta_s$ do not exceed the fraction of remote work $1-\beta_t$. When this condition is not satisfied, it is possible that WFH raises land rents close to the CBD center. When $\beta_a=\beta_t=\beta_s=\beta$, this condition is satisfied so that WFH reduces the business land rents everywhere, as shown in Figure 3.[21]

The total business land rent is given by $TR^{\text{bus}} \equiv 2\int_0^{b_1} R(y)\mathrm{d}y = \beta_s\left[\frac{1}{6}(\beta_a + \phi)\tau M^3 + \frac{1}{4}\beta_t t M^2\right]$, which decreases with smaller employee spillovers β_a, smaller office space β_s and on-site work β_t. Hence, *WFH unambiguously reduces the total land rent*. The average business land rent is given by $AR^{\text{bus}} = TR^{\text{bus}}/b_1 = \frac{1}{3}(\beta_a+\phi)\tau M^2 + \frac{1}{2}\beta_t tM$, which decreases with WFH. Finally, the average rent cost paid by firms is TR^{bus}/M, which also falls with more intense WFH. So, by adopting a WFH scheme, *firms save on office costs not only because they reduce their office space but also because rents fall in the business district.* This analysis yields the following proposition:

Proposition 5. *WFH reduces the business land rents in all CBD locations if* $\beta_t \leq \beta_s$. *WFH unambiguously reduces the total and the average business land rents, as well as the average business land cost paid by firms.*

4.4. Wages

According to the land-labor arbitrage condition (11), the equilibrium wage is equal to $w(y) = w(b_1) + \beta_t t(b_1 - y)$, so that firms must pay workers a reference wage $w(b_1)$ and compensate them for the commuting cost within the business district. Plugging the equilibrium wage at b_1 and the equilibrium value for b_1 into this expression gives the equilibrium wage at the business location y:

$$w(y) = A(b_1) - \beta_t ty = (\beta_a + \phi)\left(\alpha - \tau\beta_s \frac{M}{2}\right)M - \beta_t ty \tag{17}$$

(see Appendix A). This wage includes the full value of production at the border of the business district, $A(b_1)$. As explained above, landlords extract only the production surplus above the one realized at that border. Since firms are unable to make profits under free entry, workers extract the rest of the production value. Workers therefore reap the economies of density created by the business spillovers.

21 The assumption of fixed land use helps us get analytical results and study the competition for land between firms and workers, which is not studied in other WFH-related papers (e.g., Brueckner et al., 2022; Behrens et al., 2021). Endogenizing the use of space will not reverse the forces at play in the current model though. If, for example, firms would occupy $\beta_s y$ units of land and workers $(1+\gamma)x$, this would make the residential land rent non-linear (convex) and the business land rent more acute in the center of the city where land rents are higher (Figure 3).

WFH impacts wages through a fall in β_a, β_s and β_t. In particular, fewer interactions among employees (lower β_a) decrease wages, while smaller office space (β_s) and less frequent commuting (smaller β_t) have a positive impact on wages. Notice, though, that the wage does not compensate for the extra residential land required for the home office, γ. Although firms save office space by relocating work tasks in less expensive residential areas, there is no market force that pushes them to compensate workers for their additional expenditure.

The average wage is defined as $\frac{1}{M}\int w(y)m(y)\mathrm{d}y$. It can be successively written as $\frac{2}{M}\int_0^{\beta_s M/2} w(y)\frac{1}{\beta_s}\mathrm{d}y = A(b_1) - \frac{1}{M}tb_1^2$. It includes the productivity at the border of the business district and the average commuting cost in this district. So, WFH inherits the properties of productivity $A(b_1)$ as shown in Section 3.1. As a consequence, WFH induces the fall of wages in small cities and their rise in large cities while the relationship between employee spillover β_a and average wage is bell-shaped.

Proposition 6. *WFH reduces the average wages in small cities and raises them in large cities. Higher fractions of WFH have a bell-shaped impact on average wages.*

5. Equilibrium and optimal WFH

The above analysis shows that WFH has different impacts on prices for land and labor in the interior of cities and across them. We now discuss how citizens are affected by WFH, what their preferred fraction of WFH is, and how the latter differs from the urban planner's choice.

5.1. Equilibrium utility

The spatial equilibrium conditions (9) and (10) yield the residents' equilibrium utility

$$U^* = (\beta_a + \phi)\left(\alpha - \tau\beta_s\frac{M}{2}\right)M - \beta_t(1+\gamma+\beta_s)t\frac{M}{2} \tag{18}$$

(see Appendix A). The first term reflects the share of the production value that is passed through wages, while the second one is the commuting cost that makes the least favored worker (i.e., most distant one) indifferent to come to the job place. The first term therefore includes the positive effect of economies of business density and the second term the negative effect of commuting costs. In line with the literature, U^* increases with larger firm productivity α and lower commuting cost t and lower business travel cost τ. Now, WFH implies lower on-site presence, fewer face-to-face interactions among employees, office space savings and additional home office space. In Equation (18), larger home office space (higher γ) and lower employee spillovers (lower β_a) have a negative impact on equilibrium utility. Utility increases though with less frequent commuting/on-site presence (lower β_t) and office space savings (lower β_s). The total effect is thus ambiguous.

To investigate this ambiguity, we compare the equilibrium utility with the utility U^0 obtained in the absence of remote work ($\beta_a = \beta_s = \beta_t = 1$ and $\gamma = 0$). This gives

$$U^* - U^0 = \underbrace{-\alpha M(1-\beta_a)}_{(-)} \underbrace{+\tau\frac{M^2}{2}[(1+\phi)-(\beta_\alpha+\phi)\beta_s]}_{(+)} \underbrace{+\Big(2-\beta_t(1+\gamma+\beta_s)\Big)t\frac{M}{2}}_{(+/-)}. \quad (19)$$

The first term expresses a utility loss from lower employee spillovers. The second term reflects a utility gain related to the lower cost of interactions when the business district becomes more compact. The third term shows the utility gains associated with the commuting cost savings that occur when people commute less frequently and the city does not expand too much (i.e., $b_2 = (1+\gamma+\beta_s)\frac{M}{2} < (2/\beta_t)\frac{M}{2}$). This is because the extra land used for home office space expands the city and increases commuting distances. Finally, it is easily checked that small fractions of WFH ($\beta_a, \beta_s, \beta_t \to 1$) make this expression negative and therefore are bad for workers if WFH requires to adapt home space for work ($\gamma > 0$). Hence, a small intensity of WFH is not supported by workers if they need to increase or organize their home space by a finite amount for such work activities.

Expression (19) is an increasing function of population size M. It is positive for population sizes $M > M_1$ where M_1 is the root of its RHS and given by

$$M_1 = \frac{2\alpha(1-\beta_a) - \Big(2-\beta_t(1+\gamma+\beta_s)\Big)t}{\tau\Big(1-\beta_a\beta_s+(1-\beta_s)\phi\Big)}.$$

Therefore, WFH has a negative impact on utility for cities with population lower than M_1 and a positive effect for larger urban populations. As a result, *WFH benefits residents–workers only in large enough cities*. This reflects the properties of productivity under business spillovers and WFH. Our calibration exercise (Section 7) sheds more light on this result.

Proposition 7. *Small fractions of remote work worsen workers' utility. Remote work decreases equilibrium utility in small cities and increases it in large cities.*

5.2. Residents' best WFH choice

From the residents' viewpoint, the best living conditions are obtained when their equilibrium utility (19) is maximized. In this article, the WFH parameters ($\beta_a, \beta_s, \beta_t$) are simultaneously determined, but the workers can be assumed to choose the office presence/commuting frequency, β_t. As a consequence, we assume that β_s and β_a are defined as increasing functions of β_t. For the sake of simplicity, we focus on linear relationships, so that $\beta_s(\beta_t) = 1 + \sigma_s(\beta_t - 1)$ and $\beta_a(\beta_t) = 1 + \sigma_a(\beta_t - 1)$ where σ_s and σ_a are positive constants.

The equilibrium utility increases if and only if

$$\frac{dU^*}{d\beta_t} = -(1+\gamma+\beta_s)t\frac{M}{2} - [(\beta_a+\phi)\tau M + \beta_t t]\sigma_s\frac{M}{2} + \left(\alpha - \tau\beta_s\frac{M}{2}\right)\sigma_a M > 0, \quad (20)$$

where β_s and β_a are the above increasing functions of β_t. In this expression, the first and second terms are negative and the last one positive. Again, falls in commuting frequency and firm office space have a positive impact on equilibrium utility whereas the fall in employee spillovers has a negative impact. Since all terms fall in β_t, the above marginal utility diminishes in β_t so that there exists a unique optimal commuting frequency β_t^* that maximizes the equilibrium utility (see Appendix A). This also gives the resulting office space and employee spillovers, $\beta_s^* = \beta_s(\beta_t^*)$ and $\beta_a^* = \beta_a(\beta_t^*)$. We calculate:

$$\beta_t^* = \frac{[2\alpha\sigma_a - \phi\tau M\sigma_s - t(1+\gamma)] - [\sigma_s(1-\sigma_a) + (1-\sigma_s)\sigma_a\tau M + (1-\sigma_s)t]}{2\sigma_s(t+\tau M\sigma_a)}. \quad (21)$$

This decreases with smaller interaction value α, larger home office space γ and interactions for non-teleworkable tasks, ϕ. Intuitively, larger home office space expands the residential area and increases commuting costs, which must be compensated by less frequent commuting and therefore lower work time at the office. Also, interactions for non-teleworkable tasks are facilitated from the increased compactness of the business district caused by WFH. As firms break even under free entry, this gain is shifted to workers–residents.

This analysis allows us to study the effect of city size on the optimal WFH. If $\sigma_a = \sigma_s = 1$, and therefore $\beta_t = \beta_a = \beta_s$, it can be seen that the first bracketed term in the numerator of (21) is a decreasing function of M, while the second bracketed term is nil. Hence, residents' choice for on-site work β_t^* decreases in larger cities when all WFH parameters fall at the same rate. In Appendix A, we show that this result generalizes to any increasing linear functions of parameters ($\sigma_a, \sigma_s \neq 1$). This discussion allows us to state the following proposition:

Proposition 8. *Under linear relationships between the WFH parameters, the WFH intensity chosen by workers–residents decreases with city size.*

5.3. First best

We consider the welfare of the monocentric city from a utilitarian urban planner's viewpoint. That is, a planner who maximizes $\int U(c(x))n(x)dx$, subject to the resource constraints.[22] Given the linear utility, this amounts to maximizing the following city welfare function, which includes the firms' production minus workers' commuting cost:

$$W = 2\int_0^{b_1} A(y)m(y)\mathrm{d}y - 2\int_{b_1}^{b_2} t\beta_t|x - y(x)|n(x)\mathrm{d}x, \quad (22)$$

where again the land opportunity cost is assumed to be nil and $y(x)$ is the work location that the planner assigns to a resident living at x. After substitution, this gives

$$W = (\beta_a + \phi)\left(\alpha - \beta_s\tau\frac{M}{3}\right)M^2 - \beta_t(1+\gamma+\beta_s)t\frac{M^2}{4}.$$

The first term is equal to the total production value, while the second one is equal to the total travel cost. As a result, the planner internalizes the whole share of economies of densities. Put differently, it can be readily shown that W is equal to the sum of aggregate utility NU^* and total rents on residential and business land, $TR^{\mathrm{res}} + TR^{\mathrm{bus}}$, as defined in the

22 See Appendix A.

previous subsections. This implies that, compared with workers, the planner does not only internalize the share of production value and commuting cost that accrues to the labor factor, but she also considers the share that accrues to the land factor.

The welfare function has the same properties as the above equilibrium utility: it increases with larger α and lower t, τ, and γ. It is a bell-shaped function of M so that there exists a city size that maximizes the use of resources. A too small city does not bring enough benefits from spillovers and a too large city implies too much congestion. As above, it can be shown that, for a given $\gamma > 0$, very small fractions of WFH ($\beta_a, \beta_s, \beta_t \to 1$) are not beneficial.

We can now discuss the first-best WFH intensity that maximizes the above welfare function. For the sake of comparison, we assume the same linear relationships between the WFH parameters, $\beta_s(\beta_t) = 1 + \sigma_s(\beta_t - 1)$ and $\beta_a(\beta_t) = 1 + \sigma_a(\beta_t - 1)$. Then, welfare increases if and only if

$$\frac{\mathrm{d}W}{\mathrm{d}\beta_t} = -(1 + \gamma + \beta_s)t\frac{M^2}{4} - \left[(\beta_a + \phi)\tau\frac{M}{3} + \beta_t t\frac{1}{4}\right]\sigma_s M^2 + \left(\alpha - \beta_s\tau\frac{M}{3}\right)\sigma_a M^2 > 0, \quad (23)$$

where β_s and β_a are the above increasing functions of β_t. In this expression, the first and second terms are negative and the last one positive. Therefore, reductions in commuting frequency and firm office space increase welfare whereas decreases in employee spillovers have the opposite effect. The last expression is a decreasing function of β_t so that the welfare function accepts a unique maximum at β_t^{**}, which then determines the first-best use of space and employee spillovers, $\beta_s^{**} = \beta_s(\beta_t^{**})$ and $\beta_a^{**} = \beta_a(\beta_t^{**})$. It can be further shown that $\mathrm{d}W/\mathrm{d}\beta_t - N\mathrm{d}U^*/\mathrm{d}\beta_t > 0$ (see Appendix A). This implies that $\mathrm{d}U^*/\mathrm{d}\beta_t < 0$ when $\mathrm{d}W/\mathrm{d}\beta_t = 0$. In other words, residents have incentives to reduce their on-site presence below the first-best level. As a result, we have: $\beta_t^* < \beta_t^{**}$.

Residents have therefore an incentive to promote too much remote work. Intuitively, the planner considers the total value of production net of commuting cost, which is split between labor and land factors in equilibrium. The planner, therefore, internalizes landowner losses and is enticed to implement less intensive WFH than workers. The following proposition summarizes this discussion:

Proposition 9. *Residents desire more WFH than the social optimum.*

6. Discussion

Remote work was not widely implemented before the COVID-19 pandemic. In this section, we briefly discuss how the misalignment of short-run incentives between and within workers and firms and the lack of appropriate online tools might contribute to this fact. Finally, in the last subsection, we relax the assumption related to the inelastic demand for home office space. Analytical results can be found in Appendix B.

6.1. Short-run incentives for WFH

The above analysis holds in the long run when the land and labor markets have cleared and the business and residential land has been adjusted to the new needs for space.

However, in the short run, firms and residents do not take into account the changes in wages, land prices and city structures when deciding whether or not to switch to remote work. Here, we show that firms and workers have opposing interests about the implementation of remote work in the short run.

Consider the equilibrium in the absence of WFH where the prices of land and labor are given by $R^0(x)$ and $w^0(x)$ (the superscript 0 denotes the situation where $\beta_a = \beta_s = \beta_t = 1$ and $\gamma = 0$) and the city structure such that $b_1 = M/2$ and $b_2 = M$. In the short run, firms and workers take those prices as given.

On the one hand, when deciding about how much to work from home, workers at location x balance their lower commuting costs with their higher expenditures on home office space. The short-run utility gain is, thus, given by $\Delta U^0(x, y) = t(1 - \beta_t)(x - y) - \gamma R^0(x)$, where y is their workplace. It can be shown that this gain is negative at residential locations close to the business district b_1 and rises to positive values for residential places closer to the city border b_2 (see Appendix B). This demonstrates the conflict of interests among residents who live close to or away from the CBD.

On the other hand, when a firm independently decides about implementing WFH, it balances its land-rent savings with its potential productivity loss. When the firm embraces remote work, it restructures its land and saves the rent $(1 - \beta_s)R^0(y) > 0$ where $R^0(y)$ is given by Equation (16) and is concave and quadratic function of distance to the city geographical center y with a positive slope at the CBD center $y = 0$ (see Figure 3). By contrast, its employees meet the employees in other firms with probability $\beta_a^{1/2}$ under WFH whereas they meet them with a probability equal to 1 in the absence of it. The firm therefore loses the production value

$$\Delta A^0(y) \equiv (1 - \beta_a^{1/2}) \int_{-M/2}^{M/2} (\alpha - \tau|z - y|) m^0(z) \mathrm{d}z > 0,$$

where $m^0(z) = 1$. It can be shown that this loss is a positive, decreasing, concave and quadratic function of distance to city geographical center y with zero slope at the CBD center $y = 0$. Therefore, a firm always loses productivity by implementing WFH and loses more if it operates at the CBD geographical center. When both rent savings and productivity losses are taken into account, the net gain $\Delta\pi^0(y) = (1 - \beta_s)R^0(y) - \Delta A^0(y)$ is a quadratic function of $y \in [0, M/2]$ with positive slope at the city center $y = 0$. The function may nevertheless increase or decrease at other CBD locations. As a result, depending on parameter values, $\Delta\pi^0(y)$ can be concave or convex so that the firm may gain at the center of the CBD, at the periphery, or in every location of the CBD (see Appendix B). Hence, the model shows that WFH is not unambiguously good or bad for all firms, and a majority of them may well promote it or not. This leads to the following proposition:

Proposition 10. *Consider the short run where land rents, wages and city structure are fixed. Then, long-distance commuters have incentives to adopt WFH while short-distance ones do not. Firms' incentives are generically not aligned between themselves and with workers' preferences.*

This result is in line with Barrero et al. (2021c), who show that there is a gap between the amount of WFH preferred by firms and the one preferred by employees. It also provides an argument about the limited implementation of remote work before the COVID-19 pandemic. The implementation of WFH requires negotiations among the groups of employees and employers, which may lead to some collective agreements on WFH conditions.[23]

6.2. Advances in digital technology and WFH productivity

In this article, WFH affects the city structure, the land and the labor markets in a city where the production is characterized by business spillovers. The introduction of WFH in such a well-established framework is novel and provides intuition on how cities may be restructured with the rise of remote work. However, our analysis has ignored the significant advances in digital technology, which are redefining the working environment. Indeed, the COVID-19 pandemic has accelerated the digital transformation and facilitated the switch to remote work. New online tools allow a large number of employees to efficiently work from home and enable firms to offer their employees more flexible working schemes. We now show how our model can be extended to incorporate these advances in digital technology.

We assume here that online tools facilitate the interaction among employees and increase the productivity of the firms, but still in-person communication is preferred. The production function (3) can be redefined as

$$A(y) = \left(\underbrace{\beta_a + \phi}_{\text{on-site productivity}} + \underbrace{\lambda(1 - \beta_a)}_{\text{WFH productivity}} \right) \int_{-b_1}^{b_1} (\alpha - \tau|z - y|) m(z) \mathrm{d}z, \tag{24}$$

where β_a is re-interpreted as office work that determines the on-site productivity and the parameter $\lambda \in (0, 1)$ measures the efficiency of online tools and the contribution of WFH productivity.[24] Accordingly, WFH productivity is nil in the absence of efficient online tools ($\lambda = 0$) while it is identical to the on-site productivity in the presence of very efficient tools ($\lambda = 1$). The results of the above model can readily be extended under this setup (see details in Appendix B). In particular, the monocentric city is shown to be a spatial equilibrium if and only if $N > N_m^\lambda$ where

$$N_m^\lambda = \frac{2t}{\tau} \frac{\beta_t}{\beta_a(1 - \lambda) + \phi + \lambda} \frac{1 + \gamma + \beta_s}{1 + \gamma} < N_m,$$

and the superscript λ denotes the availability of online tools. Indeed, a higher λ decreases N_m^λ and therefore enables the emergence of monocentric cities for smaller population sizes. Hence, the more efficient online technologies facilitate the emergence of a monocentric city.

How online tools affect land rents, wages and utility? As shown in Appendix B, they do not affect the level of residential land rents because they do not change the land market conditions in the residential district and at its border with the farming land. However, better online tools increase the productivity of the firms. Under free entry and zero profits, the higher firm revenues are shifted to business land rents and wages, which raises the equilibrium utility levels, as follows:

23 Employee and company collective agreements that will regulate remote work in a post-COVID-19 Europe are discussed in EU-OSHA (2021). Such agreements are also negotiated in Canada by the Canadian Union of Public Employees: https://cupe.ca/negotiating-work-home-language-bargaining-table.

24 This is, for example, the case where $\sigma_a = 1$, in the linear relation $\beta_a(\beta_t) = 1 + \sigma_a(\beta_t - 1)$ assumed above.

$$U^*_\lambda = [\beta_a + \phi + \lambda(1-\beta_a)]\left(\alpha - \tau\beta_s\frac{M}{2}\right)M - \beta_t(1+\gamma+\beta_s)t\frac{M}{2} > U^*. \qquad (25)$$

When employees work from home, they lose utility because of lower productivity (first term) while they benefit from lower commuting costs (second term). However, when WFH contributes to productivity, $\lambda \in (0,1)$, advances in digital technology increase workers' utility. Finally, using the same argument as in the previous section, it is shown in Appendix B that both residents and urban planner choose commuting frequencies and on-site presence $\beta^*_{t\lambda}$ and $\beta^{**}_{t\lambda}$ that decrease with better online tools (i.e., higher λ). Here also, residents desire more WFH than the social optimum: $\beta^*_{t\lambda} < \beta^{**}_{t\lambda}$.

To sum up, better online tools facilitate the switch to remote work, imply lower losses in firm productivity and raise the employees' willingness to work from home. It is shown that the planner's optimal office presence follows a similar pattern with $\beta^{**}_{t\lambda} < \beta^{**}_t$. From the planner's point of view, better online tools enable savings in commuting costs and allow workers to contribute to productivity while working on the residential land. This leads to the following proposition.

Proposition 11. *Advances in digital technology that allow workers to contribute to productivity when they work from home facilitate even further the formation of monocentric cities, and increase the equilibrium business land rents and wages. They increase the optimal fraction of remote work and imply welfare benefits.*

Up to this point, we have assumed that WFH productivity is always lower than on-site productivity, that is, $\lambda \in (0,1)$. However, workers might have higher productivity at home, so that $\lambda > 1$. This could be the case for some professions, such as computer programmers. Also, higher productivity may arise through indirect channels, such as higher worker retention (see, e.g., Bloom et al., 2022). In this case, workers benefit from both productivity gains and commuting cost savings when they switch to remote work. In terms of our model, the first term in Equation (25) becomes larger (higher productivity gains) and the second term less negative (higher commuting cost savings) when WFH increases. It can be shown that workers' optimal WFH choice will be such that they limit their commute to a minimum amount.[25] This amount is related to the tasks that require office presence (as defined by ϕ) and is not modeled in this article for the sake of simplicity.

6.3. Elastic demand for home office space

In this article, we assumed an inelastic demand for home office space γ. The empirical literature establishes that WFH increases housing consumption by several percents (e.g., Stanton and Tiwari, 2021), it does not state though whether this amounts significantly varies with the fraction of WFH. Yet, the possibility of elastic demand for home-office space can alter residents' and planner's optimal WFH intensity.

To briefly study this possibility, we assume in this subsection that $\gamma \equiv \gamma_0(1-\beta_t)$. Based on this assumption, higher fractions of remote work $(1-\beta_t)$ increase housing demand, which in turn increases the size of the city and the commuting distance of workers. Also, the demand for home office space will have an impact on the equilibrium utility and welfare when WFH becomes more or less prevalent. In particular, the last term in the

25 See Appendix B.

expression of equilibrium utility (18) must now be replaced by $-\beta_t[1+\gamma_0(1-\beta_t)+\beta_s]t\frac{M}{2}$ or equivalently, $-\beta_t(1+\gamma_0+\beta_s)t\frac{M}{2}+\gamma_0\beta_t^2 t\frac{M}{2}$. While the first term reflects the WFH effect at exogenous home office space as studied above, the second one expresses the new effect due to home space endogeneity. That effect shows that more intense WFH (lower β_t) decreases equilibrium utility because people want larger home office space, which in turn expands the city and increases the commuting distance. This has an impact on the marginal utility (20) that should now be decreased by the amount $\gamma_0\beta_t tM/2$. It is then easily shown that the residents' best WFH intensity $(1-\beta_t^*)$ is higher.

A similar argument can be made for welfare. It can be shown that endogenous home space decreases the marginal welfare (23) by the amount of $\gamma_0\beta_t tM^2/4$. This is because it increases the commuting distance for the whole set of residents. This leads to a higher optimal WFH fraction, $(1-\beta_t^{**})$. In Appendix B, we show that $\beta_t^* < \beta_t^{**}$ still holds, meaning that residents desire more WFH compared to the first best.

7. Calibration exercise

To illustrate our main results, we investigate the impact of remote work on equilibrium rents, wages, production and utility by calibrating our model to a city having the characteristics of the average capital city of the EU. This exercise is important because it spots the city sizes that are compatible with a spatial equilibrium of monocentric city. The exercise also allows us to quantify the effect of increasing fractions of WFH on productivity and utility for various relationships between productivity and on-site work. WFH is shown to increase utility only in the largest European capital cities.

In particular, in this exercise, we extend the model to more realistic features of cities. First, we relax the linear city assumption and consider a circular city with the CBD lying on a disk with radius b_1 and a residential area on a ring extending to the city border b_2. In this case, each worker commutes to a firm located on the same ray while business interactions take place on the whole CBD disk. We use parameters from the literature and official data sources to calibrate the model (see details in Appendix C). More precisely, we consider that each firm employs 32 workers, which is the average number of employees in mid-size companies in EU 2017 (Eurostat 2017). Firms occupy $15\,\text{m}^2$ per employee while each household uses $90.16\,\text{m}^2$ of floor surface. We assume office buildings with six floors and residential houses with two floors. We further assume that in the interior of the city half of the space is occupied by firms and residences, and the rest is used for (unmodeled) public facilities, green areas and infrastructure such as roads, highways, etc. Commuting costs include monetary and time costs and are assessed to 0.65 euros per kilometer.[26] We use the shares of teleworkable and non-teleworkable jobs in the EU reported by the European Commission (2020) to set the parameter ϕ equal to 3. The production function is calibrated to match the average wage and population of EU capital cities with a net annual salary of 18, 242 euros, 3, 04 million inhabitants and thus 1, 32 million households. As a result, the interaction benefits and the cost of interaction per km are set to $\alpha = 0.085$ and $\tau = 0.008$. The calibrated city example satisfies the equilibrium conditions for the formation of a monocentric city.[27,28]

26 For the estimation of the commuting cost, see Appendix C.
27 For average salaries and population of EU capital cities, see Appendix C.
28 Calculation details of tables and figures are provided in the online supplementary file.

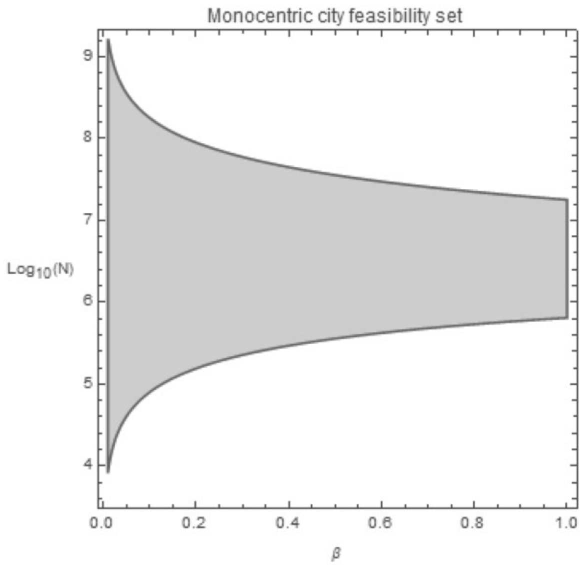


Figure 4. Monocentric city feasibility set. Population size ($\log_{10}N$) as a function of the fraction of office work β.

Figure 4 presents the feasibility set of monocentric cities as the set of population sizes (in $\log_{10}$) for which the monocentric city is a spatial equilibrium (lower boundary) and meets the assumption of global business interactions (higher boundary).[29] For simplicity, we assume here that $\sigma_a = \sigma_s = 1$, meaning that the WFH parameters take the same value: $\beta_a = \beta_s = \beta_t = \beta$. Also, we assume that remote work increases the area of residences by 7% (Stanton and Tiwari, 2021). The horizontal axis shows the fractions of on-site presence: when $\beta = 1$, individuals work full-time at the office while they work full-time at home when $\beta = 0$. The figure illustrates Proposition 1 by showing that WFH facilitates the sustainability of smaller monocentric cities (lower bound in Figure 4). It also eases the assumption of global business interactions (upper bound). This is because WFH shrinks the CBD area.

The calibration exercise can also help us assess the various effects of WFH parameters. Table 1 displays the arc elasticities of a decrease of parameters β_a, β_t and β_s, and an increase of γ, on aggregate production ($Atot$), total wages ($wtot$), aggregate business (Φtot) and residential land rents (Ψtot) and individual utility (U^*). The effects are computed on cities that initially have no WFH (i.e., $\beta_a = \beta_t = \beta_s = 1$ and $\gamma = 0$). In this model with $U(c) = c$, changes in utility can be interpreted as changes in consumption of composite goods.

Table 1(a) reports the effects on the city with 3, 04 million inhabitants as we have calibrated to average characteristics of EU capital cities. The table firstly highlights the effect

29 Equilibrium structures below the lower bound include first, partially-mixed cities and then, fully mixed cities. In fully mixed cities, every location includes a mix of workers and firms. Partially-mixed ones contain a mixed area in the geographical center and specialized areas for business and residences. In fully mixed areas, workers and firms co-locate in space. The absence of commuting makes it less interesting to study the incentives for WFH.

Table 1. Disentangling the effects of WFH.

	a. Average European Capital City (3 m inhab)				b. Largest European Capital City (12 m inhab)			
	β_a	β_t	β_s	γ	β_a	β_t	β_s	γ
Atot	–0.25	0	0.07	0	–0.25	0	0.17	0
wtot	–0.249	–0.005	0.091	0.002	–0.249	–0.003	0.232	0.001
Φtot	–0.291	0.163	–0.581	–0.079	–0.259	0.034	–0.518	–0.017
Ψtot	0	–1	0.054	0.553	0	–1	0.054	0.553
U^*	–0.285	0.141	0.095	–0.079	–0.27	0.08	0.246	–0.045

Notes: The table displays the arc elasticities of a decrease of parameters β_a, β_t and β_s, and an increase of γ, on aggregate production (*Atot*), total wages (*wtot*), aggregate business (Φtot) and residential land rents (Ψtot) and individual utility (U^*). The effects are computed on cities that initially have no WFH ($\beta_a = \beta_t = \beta_s = 1$ and $\gamma = 0$). Utility changes are equivalent to changes in composite good consumption. Each arc elasticity is computed for 1% change in the studied parameters. Parameters are calibrated with data on an average European-capital city with 3, 4 million inhabitants. Panel a reports the effects on the calibrated city. Panel b reports the effects on the city with same calibration parameters but with 12 million inhabitants.

of WFH through the channel of smaller employee spillover (β_a). A fall in β_a has a strong negative effect on production, which lowers both business land rents and wages, and then negatively affects workers' utility. Commuting cost savings mainly affect the residential land rents: a percent fall in β_t reduces residential land rents by the same percentage. It therefore mainly decreases the income of landlords owning the residential plots. Office space (β_s) savings decrease the business land rents and increase the wages. Indeed, the smaller geographical distance between firms facilitates the interactions among employees, which in turn increases their productivity and wages. Last, the effect of additional home office space (γ) is mainly apparent in the residential land rents. The need for home office space increases the size of the residential buildings and expands the residential district. As a result, total residential land rents increase. From the last row of Table 1, it can be seen that workers' utility falls because of lower employee spillovers and larger home office space and increases not only because of lower commuting cost but also lower business office space. Table 1 can further be used to approximate the magnitude of the effect of WFH parameter changes on utility and other aggregate variables.[30] For instance, a change of 1% in each WFH factor induces a fall in utility of about 0.13% in the average European capital city (i.e., $-0.285 * 1\% + 0.141 * 1\% + 0.095 * 1\% - 0.079 * 1\% = -0.13\%$). This fall is mainly due to the effect of employee spillovers.

Table 1(b) shows the same computations for the largest European capital city, Paris, that has a population of 12 million inhabitants (5.6 million households) in the metropolitan area. In this case, the benefits of WFH associated with the savings in office space are stronger. As seen in Section 3.1, the impact of WFH on city productivity hinges on its effect through employee spillovers and city compactness. WFH induces a productivity loss due to lower employee spillovers (–0.27%) and a productivity gain due to a more compact CBD (0.246%). When it comes to equilibrium utility, the overall effect of employee

30 Whereas our theoretical model predicts non-linear effects and cross effects between WFH parameters, our numerical investigations do not show strong non-linear and cross effects. Changes in β_a, β_s, β_t, and γ larger than 1% indeed lead to coefficients similar to Table 1.

spillovers, compactness of the business center and commuting cost savings is positive (approximately $-0.27 * 1\% + 0.08 * 1\% + 0.246 * 1\% = 0.056\%$). This effect remains positive but very small once the negative impact of home office space is taken into account. To sum up, the above numerical exercise shows that a common proportional fall in WFH parameters decreases the equilibrium utility (U^*) in smaller cities (such as the average European capital city of 3 million inhabitants) and has small positive effect on the equilibrium utility in larger cities. Aggregate productivity is decreased in both cases, but the positive effect of office space savings is higher in the largest city.

Table 1 gives the possibility to evaluate the effect of remote work when the WFH parameters do not change proportionally. Indeed, one may argue that commuting frequency reductions are larger than office space savings because some business activities require the simultaneous presence of a number of employees. Similarly, productivity losses may be proportionally smaller than the reduction in commuting frequency because some employees (e.g., IT workers) are still able to interact when they work from home. Finally, following the literature (e.g., Stanton and Tiwari, 2021) we can assume that remote work increases home space by about 7%. Hence, a reasonable example of two WFH days per week could be a fall of parameters β_a, β_t and β_s by 10%, 40% and 25%, respectively, and an increase of 7% for γ. This example implies a utility increase of approximately 4.6% in the average European capital city and 6.3% in the largest European capital city.[31] In this example, WFH is clearly beneficial. The weaker the spillover losses, the higher the utility gains from WFH.

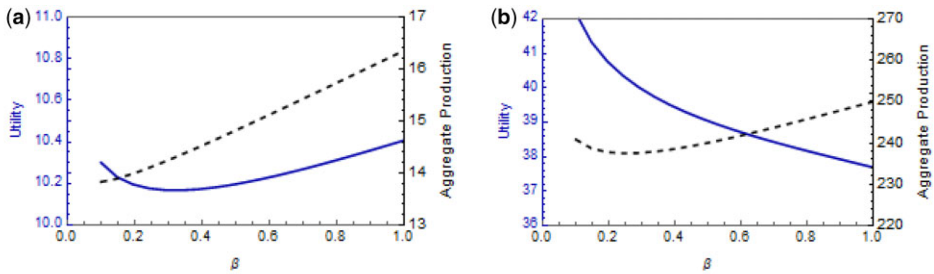
Table 1 also allows us to assess the importance of the channel of office space savings in the increase of knowledge spillovers. Indeed, spillovers do not increase if the released office space is not used for business purposes so that distances between firms do not change. In this case, WFH does not alter the parameter of office space β_s. In the previous example, this corresponds to decreases of β_a and β_t by 10% and 40%, and an increase of 7% for γ while β_s remains unchanged. Then, the utility increases only by 2.2% in the average European capital city and 0.2% in the largest European capital city. As a result, the absence of office space savings and benefits from business proximity decreases the residents' gain from WFH, in particular in the larger cities where economies of agglomeration are important. Still, in this example, residents benefit from WFH.

Table 1 therefore allows the reader to evaluate the WFH effects according to her preferred estimations of parameter changes. The key element in this discussion is the assessment of spillover loss, for which we lack robust empirical assessment. Nevertheless, Table 1 permits to obtain a higher bound for such spillover losses. Indeed, in the first example above, WFH remains beneficial for workers if employee spillovers do not fall by more than 26.2% in the average European capital city and 33.4% in the largest one.[32] In the following paragraphs, we further investigate the relationship between the WFH parameters.

Figure 5 shows equilibrium utility (blue solid curve) and aggregate production (black dashed curve) for various fractions of on-site work when all WFH parameters are identical $\beta = \beta_a = \beta_s = \beta_t$. It is shown that WFH negatively affects smaller cities, both in terms of

31 Indeed, one computes $-0.285 * 10\% + 0.141 * 40\% + 0.095 * 25\% - 0.079 * 7\% = 4.6\%$ and $-0.27 * 10\% + 0.08 * 40\% + 0.246 * 25\% - 0.045 * 7\% = 6.3\%$.

32 One verifies $\Delta\beta_a/\beta_a * 0.285 + 40\% * 0.141 + 25\% * 0.095 - 7\% * 0.079 \geq 0\%$ in the average European capital city and $\Delta\beta_a/\beta_a * 0.27 + 25\% * 0.246 + 40\% * 0.08 - 7\% * 0.045 \geq 0$ in the largest one.



Average European Capital City (3m)

Largest European Capital City (12m)

Figure 5. Individual utility (solid line, in thousand euros) and aggregate production (dashed line, in billion euros).

individual utility and aggregate production. However, in larger cities, workers benefit as their utility increases with higher fractions of WFH while firms have smaller losses.

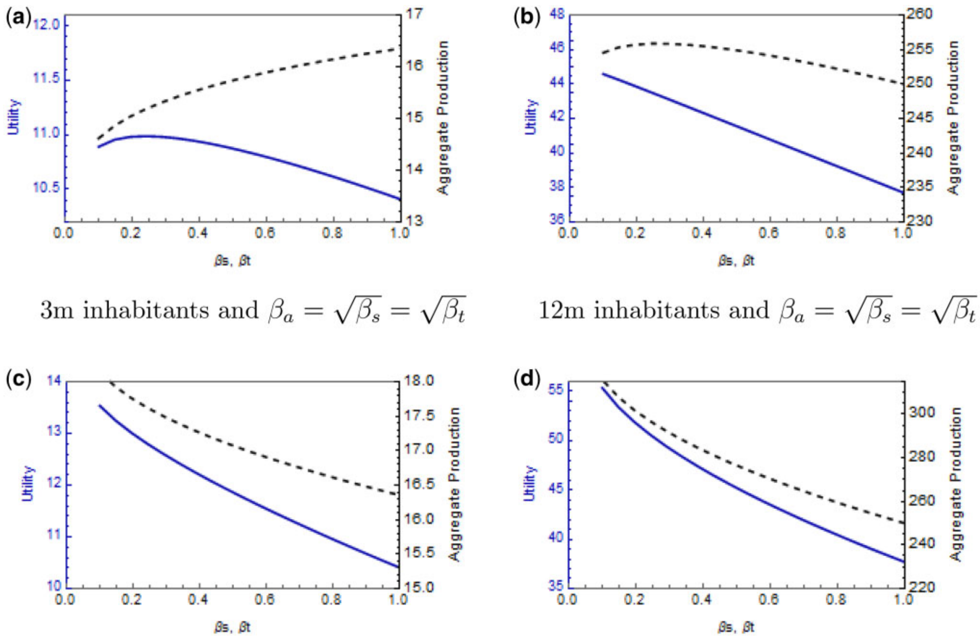
Our model up to now assumed that interactions among employees can only happen on-site and are directly related to their office presence (i.e., $\beta_a = \beta_t = \beta_s$). A reasonable alternative assumption would be that there are still employee spillovers when employees work from home (as in subsection 6.2), but the spillovers are weaker in that case. That is, $\beta_t = \beta_s < \beta_a < 1$.[33] In other words, home office workers contribute to productivity ($\beta_a > \beta_t = \beta_s$), but their contribution is lower when they work from home than when they work on site (i.e., $\beta_a < 1$). This has become possible with the advances in digital technology and the development of online communication tools. In a situation where WFH and on-site work are perfect substitutes, we will have $\beta_a = 1$. These two cases are illustrated in Figure 6, where in the first case we set $\beta_a = \sqrt{\beta_s} = \sqrt{\beta_t}$ (Figure 6(a and b)) and in the second case $\beta_t = \beta_s < \beta_a = 1$ (Figure 6(c and d)). We examine again how these two conditions affect individual utility and aggregate production both in the average and in the largest European capital city (3 and 12 million inhabitants, respectively).

It is clear that when home office workers contribute to productivity, there are utility and productivity benefits for all city sizes. Even in the smaller city, workers can now increase their utility if they share their time between remote and on-site work (Figure 6(a)). In the case of the largest city, both utility and aggregate production increase with increasing fractions of remote work (Figure 6(b)). The benefits are clearer in the case where remote workers experience no productivity losses when they work from home (Figure 6(c and d)) and increase with the city size. To conclude, our results confirm the empirical findings of Delventhal and Parkhomenko (2022) who show that there exist significant welfare benefits when workers continue to contribute to productivity when they work online as if they worked on site.

8. Conclusion

Hybrid work models will probably persist in the post-pandemic era. Employees will be expected to return to their workplaces but they will most probably be allowed to work

33 The condition $\beta_a > \beta_t, \beta_s$ is in line with Atkin et al. (2021), see Footnote 3.



3m inhabitants and $\beta_a = \sqrt{\beta_s} = \sqrt{\beta_t}$

12m inhabitants and $\beta_a = \sqrt{\beta_s} = \sqrt{\beta_t}$

3m inhabitants and $\beta_t = \beta_s < \beta_a = 1$

12m inhabitants and $\beta_t = \beta_s < \beta_a = 1$

Figure 6. Higher WFH productivity: Individual utility (solid line, in thousands) and aggregate production (dashed line, in billion).

remotely some days per week/month. This working scheme is likely to provide more advantages compared to full on-site and full remote work schemes. In this article, we study how WFH can change the internal structure and the size of monocentric cities and discuss the benefits and losses associated with the adoption of a hybrid work model.

Our results suggest that the changes in the demand for firms' and homes' office space can either shrink or expand the city size. The business area shrinks, and the business land rents decrease. The residential land rents decrease in more central locations while they may increase close to the boundaries of the city. Remote work benefits the residents of large cities. We show that workers and firms have different short-run incentives with respect to the implementation and the frequency of WFH. We discuss the effect of advances of online digital technology that increases work productivity from home. Such advances are shown to facilitate the emergence of monocentric cities and lead to increased welfare benefits.

Our analysis shows that the socially optimal level of WFH is lower than the one preferred by workers, which may require policy interventions like subsidies to office work, taxes on remote work, or defining the social WFH norm that yields the welfare-maximizing WFH level. The implementation of these or other policies needs discussion and further investigation.

The virtue of our simple model is that it permits a neat analytical discussion of WFH effects. Our model offers a stylized representation of a more complex reality of cities. As a point in case, it can be extended in several interesting directions. First, in an open city model, WFH decreases productivity in small cities and entices their workers to move away. By contrast, WFH increases the productivity of larger cities, which will attract migrants and expand their geographical extents. In other words, larger cities will attract workers farther away from their initial geographical borders. Second, if the use of space is elastic, there will be substitution between the consumption of goods and housing or between the labor input and office space, while residents and firms will use more residential land and office space where land is cheaper (for instance, at the periphery). Then, residential land rents become convex functions of the distance to the CBD, and business land rents peak at higher levels in the CBD. Figure 3 will display non-linear curves but permit the same intuitive analysis. The effects of WFH will be similar unless the use of space becomes very elastic. However, model extensions with endogenous land use do not generally lead to analytically tractable solutions (Lucas and Rossi-Hansberg, 2002), and numerical exercises on the WFH issue can be preferred (e.g., Delventhal and Parkhomenko, 2022). Finally, if firms produce goods and services that are costly to transport to consumers, they will have incentives to locate closer to residents and create new commercial subcenters in the periphery. Because WFH also entices workers to live farther away from the CBD, it will help the emergence of subcenters and the breakdown of monocentric cities.

Our model can also be extended to analyze other interesting and related issues. First, an open question in many countries is who should pay the home office expenses when people work from home. In some countries, people are able to claim tax relief on the additional costs of remote work, such as electricity, heat or broadband. There might also be some options or tax incentives for employers to cover employee expenses. Another interesting question is whether WFH is good or bad for the environment. As discussed in Larson and Zhao (2017), the savings from the lower use of energy at the office and the less frequent commuting should be compared to the higher energy use at home and the longer commuting distances. The answer to this question requires a more dedicated quantitative analysis. We leave these ideas for future research.

Supplementary material

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

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Appendix A: Theoretical model

Productivity

Using the production function (3), the business density $m(z) = 1/\beta_s$ and the values for the borders $b_1 = \beta_s M/2$ and $b_2 = (1+\gamma+\beta_s)M/2$, we derive (4) in the business district ($y \in [0, \beta_s M/2]$) as

$$\begin{aligned} A(y) &= (\beta_a + \phi)\int_{-\beta_s M/2}^{\beta_s M/2} (\alpha - \tau|z-y|)\frac{1}{\beta_s}\mathrm{d}z \\ &= (\beta_a + \phi)\left[\int_{-\beta_s M/2}^{y}\Big(\alpha - \tau(y-z)\Big)\frac{1}{\beta_s}\mathrm{d}z + \int_{y}^{\beta_s M/2}\Big(\alpha - \tau(z-y)\Big)\frac{1}{\beta_s}\mathrm{d}z\right] \\ &= (\beta_a + \phi)\left[M\alpha - \tau\left(\frac{1}{4}\beta_s M^2 + y^2/\beta_s\right)\right], \end{aligned}$$

and in the residential district ($y \in (\beta_s M/2, (1+\gamma+\beta_s)M/2]$) as

$$\begin{aligned} A(y) &= (\beta_a + \phi)\int_{-\beta_s M/2}^{\beta_s M/2}(\alpha - \tau|z-y|)\frac{1}{\beta_s}\mathrm{d}z \\ &= (\beta_a + \phi)\int_{-\beta_s M/2}^{\beta_s M/2}\Big(\alpha - \tau(y-z)\Big)\frac{1}{\beta_s}\mathrm{d}z \\ &= (\beta_a + \phi)\frac{1}{\beta_s}[(\alpha - \tau y)\int_{-\beta_s M/2}^{\beta_s M/2}\mathrm{d}z + \tau\int_{-\beta_s M/2}^{\beta_s M/2} z\mathrm{d}z] \\ &= M(\phi + \beta_a)(\alpha - y\tau). \end{aligned}$$

This is the productivity of a firm that would locate in the residential district when all other firms are located in the business district.

Total urban production is equal to:

$$\begin{aligned} TP &= \int_{-b_1}^{b_1} A(y)m(y)\mathrm{d}y \\ &= \int_{-\beta_s M/2}^{\beta_s M/2}(\beta_a + \phi)\left[M\alpha - \tau\left(\frac{1}{4}\beta_s M^2 + y^2/\beta_s\right)\right]\frac{1}{\beta_s}\mathrm{d}y \\ &= M^2(\phi + \beta_a)(\alpha - \beta_s\tau M/3) \end{aligned}$$

Within the business district, WFH decreases firm productivity if and only if $\mathrm{d}A(y) = \frac{\partial A(y)}{\partial \beta_a}\mathrm{d}\beta_a + \frac{\partial A(y)}{\partial \beta_s}\mathrm{d}\beta_s < 0$, with $\mathrm{d}\beta_a, \mathrm{d}\beta_s < 0$. One can show that

$$\frac{\partial A(y)}{\partial \beta_a} = M\alpha - \tau\left(\frac{1}{4}\beta_s M^2 + y^2/\beta_s\right) > 0,$$
$$\frac{\partial A(y)}{\partial \beta_s} = -(\beta_a + \phi)\tau\left(\frac{1}{4}M^2 - y^2/\beta_s^2\right) < 0.$$

where the terms in parentheses are positive.

In addition, *WFH decreases the firm productivity* $A(b_1)$ *at the CBD edge* ($\mathrm{d}A(b_1) < 0$) *if the city size is small enough*:

$$M \leq \frac{2\alpha}{\tau B}$$

where $B = (\beta_a + \phi)\frac{\mathrm{d}\beta_s}{\mathrm{d}\beta_a} + \beta_s > 0$ is a scalar that summarizes the expansion path of WFH parameters (β_a, β_s). Similarly, for the most central firm $y = 0$, WFH decreases the firm productivity $A(0)$ if

$$M \leq \frac{4\alpha}{\tau B}.$$

So, firm productivity falls both at the CBD center and at the edge for small enough city sizes but rises for large enough city sizes. For intermediate city sizes, it falls in the CBD center but rises at its edge. Firms at the CBD edge benefit more from the increased compactness of the CBD.

Necessary conditions, rents and wages

Using (12), the identities (9) and (10) solve for the equilibrium utility U^* and wage $w(b_1)$ as follows:

$$w(b_1) = A(b_1) - \frac{\beta_s\beta_t}{1+\gamma}t(b_2 - b_1) \tag{A1}$$
$$U^* = A(b_1) - \frac{\beta_t(1+\gamma+\beta_s)}{1+\gamma}t(b_2 - b_1) \tag{A2}$$

where $b_2 - b_1 = (1+\gamma)M/2$ and

$$A(b_1) = A\left(\frac{\beta_s M}{2}\right) = (\beta_a + \phi)M\left(\alpha - \tau\frac{\beta_s M}{2}\right). \tag{A3}$$

These conditions are used to compute the residential and business land rents.

Existence

We have to show that $\Phi(0) > \Psi(0)$. Using Equations (12), (A1) and (A2), this is equivalent to

$$A(0) - A(b_1) > \beta_t t b_1 \frac{1+\gamma+\beta_s}{1+\gamma},$$

where the LHS reflects the difference in the production of the central firm ($y = 0$) and of the firm located at the business border (b_1), while the RHS reflects commuting costs. Applying the value of the district border $b_1 = \beta_s M/2$, we have $A(0) - A(b_1) = (\beta_a + \phi)\tau(\beta_s M/2)^2/\beta_s$. Solving the inequality, we obtain

$$M > \frac{2t}{\tau}\frac{\beta_t}{\beta_a + \phi}\frac{1 + \gamma + \beta_s}{1 + \gamma},$$

which gives the minimum city size (N_m) for the emergence of a monocentric city (13).

Residential land rents

The residential rent is given by $R(x) = \Psi(x, U^*) = \frac{w(b_1) - \beta_t t(x - b_1) - U^*}{1+\gamma}$. Using Equation (A1) and (A2), the residential land rent becomes

$$R(x) = t\beta_t\frac{(b_2 - x)}{(1 + \gamma)} = \frac{\beta_t t}{1 + \gamma}\left[(\beta_s + 1 + \gamma)\frac{M}{2} - x\right]. \qquad \text{(A4)}$$

Without WFH ($\beta = 1$ and $\gamma = 0$), the residential land rent is given by $R^0(x) = t(M - x)$. Then, $R(x) \geq R^0(x)$, if and only if $x \geq x_a$, where

$$x_a \equiv \frac{1}{2}M + \frac{1}{2}M\frac{1 + \gamma - \beta_t(\gamma + \beta_s)}{1 + \gamma - \beta_t},$$

where $x_a \in (b_1, b_2) = (\beta_s M/2, \frac{M}{2}(1 + \gamma + \beta_s))$.

The house rent is equal to $(1 + \gamma)R(x)$. WFH raises the rent per residence if and only if $(1 + \gamma)R(x) > R^0(x)$. Computations show that $(1 + \gamma)R(x) \geq R^0(x)$ if $x \geq x_b$ where

$$x_b \equiv \frac{2 - \beta_t(\gamma + \beta_s + 1)}{1 - \beta_t}\frac{M}{2}.$$

We get that $x_a \leq x_b$ if and only if $\gamma \geq 1 - \beta_s$.

Business land rents

The business bid rent is given by $R(y) = \Phi(y) = [A(y) - w(b_1) - \beta_t t(b_1 - y)]/\beta_s$. Using Equations (4), (A1) and (A3), and the equilibrium values for b_1 and b_2, the business land rent becomes

$$R(y) = (\beta_a + \phi)\tau\left[\left(\frac{M}{2}\right)^2 - \left(\frac{y}{\beta_s}\right)^2\right] + t\frac{\beta_t}{\beta_s}y. \qquad \text{(A5)}$$

The business land rent decreases with smaller β_a and β_t. It decreases with smaller β_s if

$$\frac{dR(y)}{d\beta_s} = \frac{y}{\beta_s^3}[2y\tau(\phi + \beta_a) - t\beta_s\beta_t] > 0,$$

which holds true if and only if $y < \tilde{y} \equiv t\beta_s\beta_t/[2(\phi + \beta_a)\tau]$. Note that $\tilde{y} < b_1 = \beta_s M/2 \iff M > t\beta_t/[(\phi + \beta_a)\tau]$, which is true because the RHS is always smaller than N_m.

Wages

The equilibrium wage is equal to $w(y) = w(b_1) + \beta_t t(b_1 - y)$. Using Equation (A1) and $b_1 = \beta_s M/2$, we obtain Equation (17).

Equilibrium utility

Equations (A2) and (A3) give Equation (18).

Residents' best WFH choice

We now show that, under linear relationships between the WFH parameters, the WFH intensity chosen by workers–residents decreases with city size. Toward this aim, we re-write Equation (20) as

$$\frac{dU^*}{d\beta_t} = F(\beta_t, M)\frac{M}{2},$$

where

$$F(\beta_t, M) = -(1 + \gamma + \beta_s)t - [(\beta_a + \phi)\tau M + \beta_t t]\sigma_s + 2\left(\alpha - \tau\beta_s\frac{M}{2}\right)\sigma_a$$

and where β_s and β_a are the increasing functions of β_t. Note that F decreases in M and separately decreases in β_t, β_s and β_a so that $dF/d\beta_t < 0$. Then, because $dF/d\beta_t < 0$, the optimal β_t^* is given by the unique solution of $F(\beta_t^*, M) = 0$. As a consequence, $d\beta_t^*/dM = -(dF/M)/(dF/d\beta_t) < 0$ because $dF/d\beta_t < 0$ and $dF/M < 0$. Similarly, we have $dF/\alpha > 0$, $dF/t < 0$, $dF/\phi < 0$ and $dF/\tau < 0$ so that it is also confirmed that $d\beta_t^*/d\alpha > 0$, $d\beta_t^*/dt < 0$, $d\beta_t^*/d\phi < 0$ and $d\beta_t^*/d\tau < 0$.

First best

The utilitarian urban planner chooses the consumption function $c(\cdot)$, the density functions $m(\cdot)$ and $n(\cdot)$, the border b, and the WFH fraction β_t that maximize $\int U(c(x))n(x)dx$, subject to:

$$\begin{aligned} \int_{-b}^{b} c(x)n(x)dx &= \int_{-b}^{b} A(x)m(x)dx - \int_{-b}^{b} \beta_t t(x - y(x))n(x)dx \\ \int_{-b}^{b} dx &= \int_{-b}^{b}(1+\gamma)n(y)dy + \int_{-b}^{b} \beta_s m(y)dy \end{aligned}.$$

The linear utility function implies that $\int U(c(x))n(x)dx = \int c(x)n(x)dx$, so the maximization becomes:

$$\begin{aligned} &\max \int_{-b}^{b}[A(x)m(x) - \beta_t t(x - y(x))n(x)]dx \\ &\text{s.t. } \ b = (1 + \gamma + \beta_s)M/2 \end{aligned}.$$

For the monocentric city, this is equivalent to Equation (22).

We show that $dW/d\beta_t - NdU^*/d\beta_t > 0$. Assuming that $\beta_s(\beta_t) = 1 + \sigma_s(\beta_t - 1)$ and $\beta_a(\beta_t) = 1 + \sigma_a(\beta_t - 1)$, we compute

$$\frac{\mathrm{d}W}{\mathrm{d}\beta_t} - N\frac{\mathrm{d}U^*}{\mathrm{d}\beta_t} = (1+\gamma+\beta_s)t\frac{M^2}{4} + [2(\beta_a+\phi)M\tau + 3t\beta_t]\sigma_s\frac{M^2}{12} + M\tau\beta_s\sigma_a\frac{M^2}{6} > 0.$$

Appendix B: Discussion

Short-run equilibrium

Resident's choice of WFH

In the short run, equilibrium rents $R^0(x)$, wages $w^0(y)$ and locations are taken as givens and in the absence of WFH. Workers have utility equal to $U^0(x,y) = w^0(y) - R^0(x) - t(x-y)$ without WFH and $U(x,y) = w^0(y) - (1+\gamma)R^0(x) - \beta_t t(x-y)$ under WFH. Their gain from WFH is given by $\Delta U^0(x,y) \equiv U(x,y) - U^0(x,y) = -\gamma R^0(x) + (1-\beta_t)t(x-y)$. The highest gain, $\max\Delta U^0(x,y) = t(1-\beta_t)M > 0$, is obtained for the longest commuting distance $x-y=M$ when $x=M$, $y=0$ and $R^0(x) = R^0(M) = 0$. The lowest gain, $\min\Delta U^0(x,y) = -\gamma R^0(\beta_s M/2) = -\gamma tM/2 < 0$, is obtained for the shortest commuting distance $x-y=0$ while $x=y=M/2$ and $R^0(x) = R^0(M/2) = tM/2$. Hence, residents at the city edge choose WFH while those close the CBD do not.

Firm's choice of WFH

The firm's net gain is given by $\Delta\pi^0(y) = (1-\beta_s)R^0(y) - \Delta A^0(y)$ where $\Delta A^0(y) = (1-\beta_a^{1/2})(M\alpha - \tau M^2/4 - y^2\tau)$ and $R^0(y) = (1+\phi)\tau\left((M/2)^2 - y^2\right) + ty$. This gives

$$\Delta\pi^0(y) = [1-\beta_a^{1/2} - (1-\beta_s)(1+\phi)]\tau y^2 + (1-\beta_s)ty$$
$$-(1-\beta_a^{1/2})(M\alpha - \tau M^2/4) + (1-\beta_s)(1+\phi)\tau(M/2)^2.$$

This is a quadratic function of y that can be convex or concave according to the value of the first squared bracketed term and have a positive or negative intercept according to the value of the last line. Hence, according to parameter values, the profit difference can be positive everywhere, in a single interval or nowhere in the CBD support $[0, b_1]$. As a particular case, when the interaction value α is large enough, the profit difference is negative everywhere and all firms reject WFH. This is because each firm gains less from smaller office space than it loses from the lower productivity resulting from its employee spillovers. Conversely, if α is small enough, the profit difference is positive and all firms adopt WFH. The loss in employment spillovers is weaker than the rent saving in office space. As a last example, suppose that $1-\beta_a^{1/2} < (1-\beta_s)(1+\phi)$ so that $\Delta\pi^0(y)$ is a concave function of y. There exist (intermediate) values of α such that $\Delta\pi^0(y)$ takes positive values on an interval $[y_1, y_2] \subset [0, b_1]$. In this case, firms located at $y \in [y_1, y_2]$ choose WFH but other do not. A more detailed analysis is out of the scope of this article.

Advances in digital technology and WFH productivity

Under the development of online tools, the production function is given by Equation (24). Using

$$\phi' = \frac{\phi + \lambda}{1 - \lambda}, \ \alpha' = (1 - \lambda)\alpha, \ \text{and} \ \tau' = (1 - \lambda)\tau$$

the production function can be rewritten as

$$A(y) = (\beta_a + \phi') \int_{-\beta_s M/2}^{-\beta_s M/2} (\alpha' - \tau'|z - y|) \frac{1}{\beta_s} \mathrm{d}z \tag{B1}$$

which has the same structure as the one without development of online tools. So, the equilibrium properties with respect to α, τ, and ϕ can be extended in the new model with α', τ', and ϕ'.

The spatial equilibrium condition becomes $M > N_m^\lambda$ where

$$\begin{aligned} N_m^\lambda &\equiv \frac{2t}{\tau'} \frac{\beta_t}{\beta_a + \phi'} \frac{1 + \gamma + \beta_s}{1 + \gamma} \\ &= \frac{2t}{\tau} \frac{\beta_t}{\beta_a(1 - \lambda) + \phi + \lambda} \frac{1 + \gamma + \beta_s}{1 + \gamma}. \end{aligned} \tag{B2}$$

One can readily show that N_m^λ in Equation (B2) is lower than N_m in Equation (13). Therefore, the development of online tools decreases N_m^λ, which expands the set of equilibrium monocentric cities.

The business land rent is given by

$$\begin{aligned} R^\lambda(y) &= \frac{\beta_a + \phi'}{\beta_s^2} \tau' \left[\left(\frac{\beta_s M}{2} \right)^2 - y^2 \right] + t \frac{\beta_t}{\beta_s} y \\ &= \frac{\beta_a + \phi + \lambda(1 - \beta_a)}{\beta_s^2} \tau \left[\left(\frac{\beta_s M}{2} \right)^2 - y^2 \right] + t \frac{\beta_t}{\beta_s} y, \end{aligned} \tag{B3}$$

which increases with higher λ. Hence, the development of online tools increases business land rent.

The wage is equal to

$$\begin{aligned} w^\lambda(y) &= (\beta_a + \phi') M \left(\alpha' - \tau' \beta_s \frac{M}{2} \right) - t\beta_t y \\ &= \Big(\beta_a + \phi + \lambda(1 - \beta_a) \Big) M \left(\alpha - \tau\beta_s \frac{M}{2} \right) - t\beta_t y, \end{aligned} \tag{B4}$$

which also increases with higher λ. The development of online tools increases wages.

The equilibrium utility U_λ^* is given by

$$\begin{aligned} U_\lambda^* &= (\beta_a + \phi') M \left(\alpha' - \tau' \beta_s \frac{M}{2} \right) - \beta_t (1 + \gamma + \beta_s) t \frac{M}{2} \\ &= \Big(\beta_a + \phi + \lambda(1 - \beta_a) \Big) M \left(\alpha - \tau\beta_s \frac{M}{2} \right) - \beta_t (1 + \gamma + \beta_s) t \frac{M}{2} \end{aligned} \tag{B5}$$

which rises with λ. The development of online tools increases utility.

The utility maximizing on-site presence is then obtained by

$$\begin{aligned}\frac{\mathrm{d}U_\lambda^*}{\mathrm{d}\beta_t} &= -(1+\gamma+\beta_s)t\frac{M}{2} - [(\beta_a+\phi')\tau' M + \beta_t t]\frac{M}{2}\sigma_s + \left(\alpha' - \tau'\beta_s\frac{M}{2}\right)M\sigma_a \\ &= -(1+\gamma+\beta_s)t\frac{M}{2} - [\left(\beta_a(1-\lambda)+\phi+\lambda\right)\tau M + \beta_t t]\frac{M}{2}\sigma_s \\ &\quad +(1-\lambda)\left(\alpha - \tau\beta_s\frac{M}{2}\right)M\sigma_a \\ &= 0,\end{aligned}$$

where β_s and β_a are the linear increasing functions of β_t defined in the text. The second expression decreases in both λ and β_t. Then, the optimal office presence $\beta_{\lambda t}^*$ falls with higher λ; that is, with better online tools. It can be verified that $\beta_{\lambda t}^* < \beta_t^*$. Note that, if $\lambda > 1$, all terms in the second expression are negative so that $dU_\lambda^*/d\beta_t < 0$, for all admissible β_t. This implies that workers want to have the lowest commuting frequency.

The welfare is given by

$$W^\lambda = (\beta_a+\phi')\left(\alpha' - \beta_s\tau'\frac{M}{3}\right)M^2 - t\beta_t(1+\gamma+\beta_s)\frac{M^2}{4}. \tag{B6}$$

The welfare-maximizing on-site presence is obtained by

$$\begin{aligned}\frac{\mathrm{d}W^\lambda}{\mathrm{d}\beta_t} &= -(1+\gamma+\beta_s)t\frac{M^2}{4} - \left[(\beta_a+\phi')\tau'\frac{M}{3} + \beta_t t\frac{1}{4}\right]\sigma_s M^2 + \left(\alpha' - \beta_s\tau'\frac{M}{3}\right)\sigma_a M^2 \\ &= -(1+\gamma+\beta_s)t\frac{M^2}{4} - \left[\left(\beta_a(1-\lambda)+\phi+\lambda\right)\tau'\frac{M}{3} + \beta_t t\frac{1}{4}\right]\sigma_s M^2 \\ &\quad +(1-\lambda)\left(\alpha - \beta_s\tau\frac{M}{3}\right)\sigma_a M^2 \\ &= 0\end{aligned}.$$

where β_s and β_a are the linear increasing functions of β_t defined in the text. Since the second expression is decreasing in β_t and λ, the first best $\beta_{\lambda t}^{**}$ falls with λ. More efficient tools entice the planner to choose more WFH. One can furthermore check that

$$\frac{\mathrm{d}W}{\mathrm{d}\beta_t} - N\frac{\mathrm{d}U^*}{\mathrm{d}\beta_t} = (1+\gamma+\beta_s)t\frac{M^2}{4} + [2(\beta_a+\phi')M\tau' + 3t\beta_t]\sigma_s\frac{M^2}{12} + M\tau'\beta_s\sigma_a\frac{M^2}{6} > 0.$$

So, $\mathrm{d}W/\mathrm{d}\beta_t = 0$ implies $\mathrm{d}U^*/\mathrm{d}\beta_t < 0$. Workers want a smaller commuting frequency than the planner does. So, $\beta_{\lambda t}^* < \beta_{\lambda t}^{**}$.

Elastic demand for home office space

To show that $\beta_t^* < \beta_t^{**}$ still holds, we compare the impact on the marginal utility aggregated for all residents ($\gamma_0\beta_t tM/2 * M$) and the one on the marginal welfare ($\gamma_0\beta_t tM^2/4$). Since residents travel less than the resident at the city edge, $\gamma_0\beta_t tM^2/4 < \gamma_0\beta_t tM/2 * M$. Hence, as γ_0 rises, the marginal welfare decreases at a smaller pace than the aggregate equilibrium utility so that the planner's choice β_t^{**} decreases more slowly than the residents' choice β_t^*. This means that even with elastic demand for home office space, residents desire more WFH compared with first best, $\beta_t^* < \beta_t^{**}$.

Appendix C: Calibration

In this appendix, we report our choice of calibration values.

Building sizes and household size in Europe

Average building sizes in Europe are provided by Economidou et al. (2011). Firms occupy $s_f = 15\ m^2$ per employee while each household uses $s_r = 90.16\ m^2$ of floor surface. Remote work increases the size of the apartment by 7%, which implies $\gamma = 6.3\ m^2$ (Stanton and Tiwari, 2021). The size of the apartment is calculated considering the average household size in Europe in 2017 that was 2.3 persons.[34]

Using World Bank indicators,[35] we calculate the labor force as a percentage of the total population in EU 2017. This amounts to 0.48, which corresponds to 1.09 workers per household. For simplicity, we can therefore assume that there is one worker per household.

Commuting cost

To estimate the commuting cost, we follow Borck and Brueckner (2018). We thus use the EU 2019 median hourly wage of 21.5 euros and value the opportunity cost of time at 50%, that is, 10.75 euros/hour.[36] Assuming an average speed of 40 km/h, this implies an opportunity cost of time during commuting of 0.28 euros/km. The monetary cost of owning a car is estimated to 0.37 euros/km in Europe by Roadzen Insurance Company for the year of 2019.[37] This includes vehicle depreciation, taxes, registration fees, insurance, maintenance, car finance charges and fuel. Hence, we estimate the total cost of commuting to 0.65 euros/km. Assuming 220 working days per year, this gives a commuting cost parameter equal to $t = 440 * 0.65/1000$ euros/m/year.

Average wage and population in EU capital cities

We use the average annual net salary of 26 EU capital cities calculated based on the average monthly net salaries reported in Numbeo.[38] For population, we use data from OECD statistics and we calculate the average population of 26 EU capital cities in 2017 (which excludes Valletta and Nicosia for data availability purposes). The average population is 3,040,993. This corresponds to $N =$1,322,170 households given the average household size of 2.3.

Production function

As analysed in Section 7, each firm employs $n_a = 32$ workers (average number of employees in mid-size companies in EU 2017). We consider the percentage of EU employment (65%) that is non-teleworkable because it requires a significant amount of social interactions and

34 See https://www.statista.com/statistics/1231406/average-household-size-in-europe.

35 See https://data.worldbank.org/indicator/SL.TLF.TOTL.IN?locations=EU&most_recent_.year_desc=false.

36 For the EU median hourly wage, see Eurostat data, https://ec.europa.eu/eurostat/databrowser/view/lc_lci_lev/default/table?lang=en.

37 See https://roadzen.medium.com/the-real-cost-of-owning-a-car-eu-efa814dde33a.

38 See https://www.numbeo.com/cost-of-living/region_prices_by_city?itemId=105&region=150&displayCurrency=EUR.

the percentage (22%) that is teleworkable but still requires a lot of social interaction (see Table 1, European Commission, 2020). The ratio of non-teleworkable over teleworkable jobs is then given by $\phi/1$ in the model and $0.65/0.22 = 2.96$. So, we round ϕ to 3. The production function is calibrated to match the average wage and population of EU capital cities. Thus, the interaction benefit is set to $\alpha = 0.085$ and the cost of interaction per km is $\tau = 0.008$.

Calibration

In the extended model used in the calibration, the budget constraint (1) becomes:

$$c(x) + (1+\gamma)s_r R(x) + \beta_t t\|z-y\| \leq w(y), \tag{C1}$$

where $\|z-y\|$ is the distance between the two vectors z and y. The firm's profit is given by

$$\pi(y) = A(y) - \beta_s s_f R(y) - n_a w(y). \tag{C2}$$

Finally, the production function becomes

$$A(y) = n_a(\beta_a + \phi)\int_{z\in D}(\alpha - \tau\|z-y\|)m\mathrm{d}z, \tag{C3}$$

where $m = 1/(\beta_s s_f)$ and D is the disk with surface equal to $Infr * m\frac{N}{n_a}$. Assuming that half of the space is occupied by firms and residences and the rest is used for infrastructure, green areas and public facilities imply $Infr = 2$.

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