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The impact of working from home arrangements on urban sprawl when the firms pay for the "home office"

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Abstract: Following the Covid-19 pandemic, many working from home (WFH) arrangements have been contracted between firms and working households. While firms can save space at the workplace, additional housing surface areas are required for home-based activities. Can these partial transfers of activities from work- to residential places be compatible with urban sprawl containment? In this paper, we use a standard urban economics monocentric model to determine the extent to which urban sprawl containment may be achieved despite WFH, depending on the type of agent that pays for the additional housing costs required for home-based activities. We compare three WFH scenarios with a reference case without WFH: (1) If additional housing costs are entirely paid by households, (2) If such costs are entirely paid by firms, and (3) If they are partially paid by firms (for the share of home-based activities only). We emphasize two main results: first, a better urban sprawl containment is achieved in the case where households pay for the additional housing surface areas required to perform home-based activities, compared to the case where firms partially or totally pay for these additional costs; second, urban sprawl containment may even be better achieved in this scenario compared with the reference case (without WFH arrangements) at a specific double condition that must be fulfilled by the wage rate.

Keywords: Working from home ; Home-based activities; Urban sprawl; Urban economics; Monocentric model; Commuting cost

1. Introduction

The Covid-19 pandemic has emphasized the benefits and risks of WFH (working from home), amplifying the practice on both individual and collective levels. On an individual level, households benefiting from a WFH arrangement save time and money by avoiding all or part of commuting trips. On the other hand, they bear the risk of isolation. Firms can save space in the workplace, but there is no consensus on the impact of WFH on employee productivity levels. On a collective level, as the WFH organization requires a larger amount of housing to perform the share of home-based activities, part of the working surface areas are redistributed from the Central Business District (CBD) to the residential suburbs. WFH arrangements thus lead to the risk of additional urban sprawl. At the same time, the relaxation of the constraint on commuting costs for telecommuting households acts in a similar way, through both temporal and monetary levers.

Seminal theoretical papers addressing the issue of WFH or telecommuting (home-based or telecentre telecommuting) date from the early 1990s. A distinction have been made between traditional (e.g. seamstresses) and new types of home-based activities enabled by technological progress. The diffusion of personal computers and advances in office automation renewed the research question on home-based activities (Higano and Orishimo 1990, Huws 1990, Lund and Mokhtarian 1994, Kim 1997). In the 2000s, thanks to the rapid joint deployment of the Internet on the one hand, and the cell phone on the other, firms have seen their ability to offer more diverse home-based activities to some of their employees (Safirova 2002, Crandall and Gao 2005, Jiang 2008, Rhee 2008 and 2009). Continued advances in connectivity have then ensured that remote employees could benefit from reliable video conferencing connections that have allowed not only isolated home-based activities, but also collaborative ones (Larson and Zhao 2017, Messenger 2019). Finally, a recent group of papers have framed the research question of WFH in a pandemic setting where the emergence of the Covid-19 epidemic in early 2020 forced many supposed non-teleworkable functions to finally be (Belzunegui-Eraso and Erro-Garcés 2020, Kyriakopoulou and Picard 2022, Marz and Sen 2022, Delventhal et al. 2022, Toshitaka et al. 2022, Brueckner et al. 2023).

In this paper, we investigate an original mechanism for financing the additional housing surface area required for home-based activities, considering that firms take on this financing, totally or partially. We mobilize a standard urban economics monocentric model to focus on the effects of introducing a share of WFH on urban sprawl. A better containment of urban sprawl is sought by public authorities, as it causes excessive land artificialization in the vicinity of the city and increases travel distances and the negative externalities associated with transport. In this paper, we compare respective impacts on urban sprawl of introducing WFH in scenarios where the employer does not, partially does or does pay for the additional cost associated with the housing surface area required to perform home-based activities. To our knowledge, this topic has never been addressed in the urban economics literature.

We emphasize two main results:

- (1) Urban sprawl containment is better achieved in the first scenario (coverage of additional housing costs by households) compared with the two other ones.
- (2) Moreover, urban sprawl containment could be better achieved in the first scenario than in the reference case (without WFH arrangements), at a specific double condition that must be fulfilled by the wage rate. A numerical application is needed to confirm this statement.

The rest of the paper is structured as follows: we detailed the literature review considering WFH in urban economics modelling in Section 2. Our theoretical framework is presented in Section 3. We analytically solve the standard monocentric model with WFH and highlight some results in Section 4. Section 5 discusses our results and concludes.

2. Literature review

Previous studies in urban economics literature aimed at measuring the impact of a given share of home-based telecommuting (or telecenter-based telecommuting) on (1) annual commuting distances and associated pollutant emissions, and/or (2) the relocation choices of agents, mostly households but possibly firms (Rhee 2009, Delventhal et al. 2022, Tsuboi 2022). Brueckner et al. (2023) focuses on inter-city residential relocation, considering different productivity levels. Residential relocation causes

housing prices to fall in productive places and rise in the disadvantaged cities that receive the WFH migrants. By contrast, when cities differ only in amenities, workers move to high amenity cities under WFH while keeping their jobs in low-amenity cities. Housing prices then rise in the advantaged, high-amenity cities while falling in disadvantaged cities. Different city sizes can be considered. Kyriakopoulou and Picard 2022 find that WFH raises urban productivity and average wages only in large cities.

In the mentioned papers, the theoretical framework of the standard monocentric model has been favored. Some papers address the same research question of considering WFH in urban economics modelling through the lens of Quantitative Spatial Models (QSM) (Behrens et al. 2021, Delventhal et al. 2022). A few empirical papers also use local databases to measure the magnitude of relocation effects after the implementation of WFH (Liu and Su 2021, Ramani and Bloom 2021).

The results most often confirm the research assumption tested, i.e. the existence of residential relocation effects at a greater distance from the CBD after the implementation of WFH. Such household behavior acts as a rebound effect on the expected gains in annual commuting distances (and associated emissions). The net effect, however, depends on a number of variables and parameters that are convenient to vary in a monocentric model.

Our contribution comes close to Kyriakopoulou and Picard (2022). However, it could differ in several respects by incorporating alternative assumptions into the model. A major difference lies in the fact that land surface areas consumed by households and firms are fixed to unity in Kyriakopoulou and Picard (2022), whereas they can vary freely in our model. We rely on the framework developed in Le Boennec (2014) that enables the formation of an endogenous CBD. Relaxing the assumption of fixed lot sizes allows a sound understanding of the mechanisms impacting the respective sizes of the CBD and the entire city, conditioning urban sprawl containment.

3. Theoretical framework

3.1. A standard urban economics monocentric model with endogenous center

In this paper, we mobilize a theoretical urban economics framework *à la* Ogawa and Fujita (1980) based on the study of a standard monocentric model. *We take as an assumption the monocentric pattern and seek to verify its conditions of application if households benefit from a share of home-based activities.* Effects are expected on the size of the city reached after the introduction of WFH, conditioning possible urban sprawl. *We also seek to test the assumption that such effects would differ depending on whether the firms pay entirely, partially or do not pay for the additional housing surface area required to perform home-based activities.*

We consider the standard assumption of a linear monocentric city centered around $x=0$ and extending from $-b_1$ to b_1 (Figure 1).

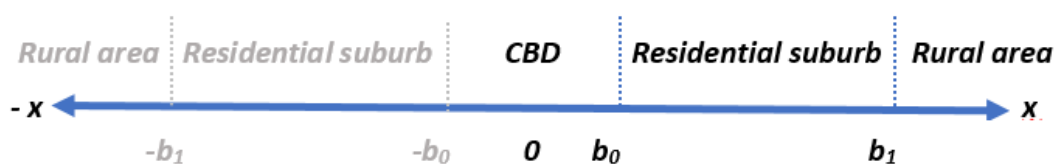


Figure 1. The linear monocentric city with endogenous center

Source : From Le Boennec (2014)

Without loss of generality, we are interested in the right half of the city. The city is defined as the union of a Central Business District (CBD) where firms are located ($x \in [0, b_0]$), and a residential suburb where households are located ($x \in [b_0, b_1]$). b_0 is defined as the CBD limit, and b_1 as the city boundary. Following Le Boennec (2014), *the city is considered with an endogenous center, i.e., the land surface areas consumed by households and firms are not fixed: they are allowed to vary freely.*

3.2. Program of the household benefiting from WFH

In this subsection, we consider the possibility for households to benefit from a share λ of home-based activities, who no longer perform these activities at their usual workplace.

For their residential location at $x \in [b_0, b_1]$ (Figure 1), N homogenous working households arbitrate between the unitary land price R (price per unit of surface area) and a given unitary travel cost c (cost per unit of distance travelled). Following the seminal paper of Alonso (1964), R is expected higher close to the CBD, conditioning potential higher housing costs, whereas c implies higher commuting costs for remote locations. At any distance x from the CBD, any household i reaches a utility level U_i , which depends on a quantity of housing S_h (acquired or rented) and a fraction Z_i of a composite good Z , encompassing the rest of the goods consumed in the (closed) economy over a period such that:

$$U_i = f(S_h, Z_i) \forall h, i \in [1, N] \quad (1.1)$$

We assume a utility function with complementary goods *à la* Le Boennec (2014) such that¹:

$$U_i(S_h, Z_i) = \min\{\delta S_h, \gamma Z_i\} \delta \geq 0, \gamma \geq 0 \quad (1.2)$$

Because of the complementarity of goods, households reach in all locations an equilibrium utility level U^* by consuming the quantities $S_h^* = U_i^*/\delta$ and $Z_i^* = U_i^*/\gamma$ such that:

$$S_h^* = \frac{\gamma}{\delta} Z_i^* \quad (1.3)$$

S_h^* and therefore Z_i^* are supposed to vary freely depending on the land price R , and thus of the distance x from the CBD.

Each household offers a quantity of work L_i to the firm that employs him/her. This quantity is set to one unit per period. *All households are likely to benefit from a share λ of home-based activities per period*, independently of their qualification (and hence of their income level). This assumption is clearly

¹ Models with exogenous centers and fixed land surface areas eventually consider utility functions with a single argument, the composite good (Kyriakopoulou and Picard, 2022). We must use a simpler specification that allows for a joint consideration of the amount of composite good and the amount of land consumed. The complementary form assumes that the consumption of the composite good evolves in the same direction as the housing surface area. It thus consists in higher furnishing expenditures, energy costs, service and maintenance costs, tax burden...when the housing surface area increases.

misleading. However, it should be remembered that we are studying the evolution of the city size following the introduction of a share of WFH; we do not process a spatial distribution of households benefiting or not from a WFH arrangement.

In this paper, we assume that the WFH organization requires a larger amount of housing to perform the share of home-based activities. In each period, the new quantity of land occupied for housing is composed of an initial reference surface area S_h , used for domestic purposes, and an additional surface area $\varepsilon > 0$, independent of the initial surface area and identical for all telecommuters, used for performing the home-based activities such that:

$$S_h' = S_h + \varepsilon \quad (2)$$

This additional surface area ε can be used, outside of working time, for domestic or leisure activities. It therefore plays a positive role in the household's utility, whether or not this additional surface area is paid by the firm. *We assume that the household overestimates the satisfaction associated with this additional surface area by integrating all of ε as an argument in the utility function* (and not just the share used during non-working time). In the absence of WFH when $\lambda = 0$, $\varepsilon = 0$ and $S_h' = S_h$.

Due to household homogeneity, each quantity of labor L_i is paid by an employing firm j at the given single wage rate w . Following Kyriakopoulou and Picard (2022), we assume that equilibrium is pre-established in the labor market. Any household i residing at $x \in [b_0, b_1]$ is subject to a generic budget constraint of the form:

$$w L_i - 2(1 - \lambda)cx = p Z_i + R(x)(S_h + \varepsilon) \quad (3.1)$$

The additional housing surface area ε is incorporated in the budget constraint as an additional cost that the household will initially face (see Subsection 4.2). The household's income consists solely of the amount of labor provided, from which it must deduce the cost of commuting on days when s.he travels from his.her residential location $x \in [b_0, b_1]$ to his.her workplace located within the CBD (considering a factor of 2 for the round trip). For simplicity, we assume that commuting costs are identical to any

workplace located within the CBD, differing only by the place of residence. Commuting cost is reduced, relative to the standard monocentric model, in proportion to the share of WFH. Each household allocates his/her income net of commuting costs between his/her expenditures on housing surface areas and the composite good. The household budget constraint is considered to be saturated at any period (no saving).

For $L_i=1$, each household i therefore pays, at any location $x \in [b_0, b_1]$, a price $R(x)$ per unit of surface area such that:

$$R(x) = \frac{w - pZ_i - 2(1-\lambda)cx}{S_h + \varepsilon} \quad (3.2)$$

3.3. Program of the firm offering WFH to its employees

M homogeneous firms locate within the CBD at $y \in [0, b_0]$ (Figure 1). Each firm produce an identical fraction Z_j of the composite good Z , such that $\sum_{j=1}^M Z_j = Z = \sum_{i=1}^N Z_i$. Put another way: we assume that the market clearing for the composite good is pre-established (Le Boennec, 2014). The profit function $\pi_j(y)$ of any firm j located at y depends on the quantity of composite good Z_j produced at a normalized unit p in equilibrium ($p=1$). Each firm must deduce from its profit a quantity of land S_f rented or acquired at a location y at the unitary price $R(y)$, as well as the wages paid for the L_j units of labor performed by the households at the unitary price w . Moreover, all firms are subject to the following production function:

$$Z_j = f(S_f, L_j) \quad (4.1)$$

The inputs of the production function consist only of a quantity of land S_f and a quantity of labor L_j . For simplification purposes, a complementary form for the production function is retained:

$$Z_j = \min\{\alpha S_f, \beta L_j\} \quad (4.2)$$

The quantities of land and labor consumed are then related by:

$$S_f = \frac{\beta}{\alpha} L_j \quad (4.3)$$

With the implementation of a WFH arrangement, the amount of land occupied by any firm j consists of an amount of land acquired or rented by the firm S_f prior to the implementation of WFH, plus the additional amount of land ε individually needed by the L_j employees to perform the home-based activities such that:

$$S_f' = S_f + \varepsilon L_j \quad (5)$$

Similarly to households, any firm considers the entire surface area εL_j in the production function in addition to the initial surface area S_f , even for the time of non-working activities. In the absence of WFH, $S_f' = S_f$. The firm's generic profit function is then written as:

$$\pi_j(y) = Z_j - w L_j - R(y)[S_f + \varepsilon L_j] \quad \forall j \in [1, M] \quad (6)$$

The equilibrium resulting from the assumption of the additional housing costs εL_j paid by the firms will be studied in Subsection 4.3. We set $Z_j = 1$, such that each firm produces one unit of composite good. Moreover, the long-run equilibrium condition implies $\pi_j(y) = 0$. At any location $y \in [0, b_0]$ within the CBD, we deduce from (6) that each firm is willing to offer a price R for one unit of land such that:

$$R(y) = R_y = \frac{1-w L_j}{S_f + \varepsilon L_j} \quad (7)$$

The profit function is independent of the location y : this is not troublesome if we consider the surface area dedicated to CBD negligible relative to the total size of the city (Kyriakopoulou and Picard, 2022).²

In the next section, we will proceed to the analytical resolution of the standard urban economics monocentric model, without then with WFH. The list of variables and parameters used is summarized in Table 1.

² Alternatively, agglomeration economies could have been introduced in the form of an accessibility function that would have explicitly taken into account distances within the CBD. This is not the purpose of this study.

Table 1. List of the variables used in the model

Variable	Description	Type	Unit
b_0	CBD limit	Explained	Meter
b_1	City boundary	Explained	Meter
S_h	Surface areas consumed by any household i	Explained	Squared Meter
S_f	Surface areas consumed by any firm j	Explained	Squared Meter
ε	Additional surface area required for home-based activities	Explanatory	Squared Meter
L_i	Quantity of labor offered by a household i	Explanatory	Hour / Fixed to 1
L_j	Quantity of work required by a firm j	Explained	Hour
Z_i	Quantity of composite good consumed by a household i	Explained	Number
Z_j	Quantity of composite good produced by a firm j	Explanatory	Number / Fixed to 1
M	Number of firms in the CBD	Explanatory	Number
N	Number of households in the residential suburb	Explanatory	Number
p	Unitary price of the composite good	Explanatory	Euro / Fixed to 1
R_a	Agricultural land rent	Explanatory	Euro/m ²
$R(x), R(y)$	Unitary land price at a distance x (resp., y) from the CBD	Explained	Euro/m²
$\psi_i(x), \phi_j(y)$	Respective bid-rent functions of any household i located at x and any firm j located in y		
w	Wage rate	Explanatory	Euro/Period
c	Unitary travel cost	Explanatory	Euro/m
λ	Share of home-based activities	Explanatory	Number
$\pi_j(y)$	Profit of any firm j located in y	Explanatory	Euro / Fixed to 0

Source: Author

Note: CBD = Central Business District

4. Model resolution

In this section, we analyze the impacts of four scenarios of WFH arrangements on urban sprawl. We in this model seek to observe the variation of the equilibrium value of the city boundary b_l from one scenario to another :

- **Reference case** (S_0): No WFH arrangement (standard urban economics monocentric model)
- **Scenario 1** (S_1): WFH arrangement with additional housing surface areas *entirely paid by households* (no coverage by firms)
- **Scenario 2** (S_2): WFH arrangement with additional housing surface areas *entirely paid by firms*
- **Scenario 3** (S_3): WFH arrangement with additional housing surface areas *partially paid by firms (and partially by households)*

At the end, we will select the scenario providing the best containment of urban sprawl, and compare it to the reference case S_0 .

The implications of the assumptions made on WFH arrangements in the four scenarios on the economic agents' behavior is summarized in Appendix 1.

4.1. Reference case: equilibrium of the model in the absence of working from home arrangements

We begin by reminding the *equilibrium conditions* of the monocentric model without WFH ($\lambda = 0$). The absence of WFH arrangements implies the absence of additional housing surface area required for home-based activities, such that $\varepsilon = 0$ and $S_h' = S_h$.

The equilibrium in the composite good market is characterized by demand-supply equality, each firm producing one unit of composite good:

$$NZ_i^* = M \tag{8.1}$$

Moreover, since each household offers one unit of labor per period, the labor market clearing imposes :

$$M = \frac{N}{L_j^*} \quad (8.2)$$

At any distance x from the CBD, a bid-rent mechanism *à la* Alonso (1964) is set up such that at any location, the agent offering the highest bid-rent occupies the land. Three standard conditions characterizing the equilibrium on the land market must be satisfied (Ogawa and Fujita, 1980):

$$\phi_j(x, 0) \geq \psi_i(x, U^*) \quad \forall x \in [0, b_0] \quad (9.1)$$

$$\psi_i(x, U^*) \geq \phi_j(x, 0) \quad \forall x \in [b_0, b_1] \quad (9.2)$$

$$\psi_i(b_1, U^*) = R_a \quad (9.3)$$

$\phi_j(x, 0)$ is the bid-rent offered by a firm j achieving zero profit at location x . $\psi_i(x, U^*)$ is the bid-rent offered by a household i achieving equilibrium utility U^* at the same location x . R_a is the agricultural land rent (the unitary price of land beyond the city boundary). R_a is assumed independent of the distance to the city center. Moreover, the respective locations of the two types of agents in either the CBD or the residential suburb further imply the following standard spatial conditions in equilibrium:

$$MS_f^* = 2b_0 \quad (10.1)$$

$$MS_f^* + NS_h^* = 2b_1 \quad (10.2)$$

We can therefore: first, equalize the household's bid-rent function at b_1 (the city boundary) with the agricultural land rent R_a , by combining (3.2) and (9.3); then, use (10.1) and (10.2) and combine them with the condition for the labor market clearing (8.2); and last, use the relationships between the arguments of the utility and the production functions (1.3) and (4.3), respectively, to finally determine the equilibrium values of L_j^* , Z_i^* , S_f^* , S_h^* , b_0 and b_1 . The four last explained variables are those that interest us in characterizing variations in urban sprawl from one scenario to another. They are written in terms

of the explanatory variables M, N, w, L_i, Z_j, R_a and the parameters.³ In the case of a standard urban economics monocentric model without WFH, we obtain the following equilibrium values:

$$S_f^{*f} = S_f^* = \frac{\beta N}{\alpha M} \quad (11.1)$$

$$S_h^{*f} = S_h^* = \frac{\gamma(\alpha w - \beta c N)}{\alpha(\delta + \gamma(cN + R_a))} \quad (11.2)$$

$$b_0 = \frac{\beta N}{2\alpha} \quad (11.3)$$

$$b_1 = \frac{N(\beta(\delta + \gamma R_a) + \alpha \gamma w)}{2\alpha(\delta + \gamma(cN + R_a))} \quad (11.4)$$

With homogenous households in terms of preferences and incomes, the equilibrium quantities of housing and the composite good (not reported here) are identical for all. The bid-rents functions of the two types of agents can be calculated from (3.2) and (7). We verify the decreasing relationship of the unitary land price R with the distance to the CBD, under the following condition: $w > \frac{\beta}{\alpha} cN$.

With a given number M of firms, the CBD limit b_0 depends positively on the population N and negatively on the total number of firms M . The city boundary b_1 grows with the wage rate w and the population N . It decreases with the unitary travel cost c . The relationship with R_a is negative under the previous condition: $w > \frac{\beta}{\alpha} cN$.

4.2. Scenario 1: equilibrium of the model with home-based activities: additional housing costs paid by households

In the three following scenarios, we are interested in the observation of possible additional urban sprawl following the introduction of a share of home-based activities λ per period, such that $\lambda > 0$. In this first scenario (S_1), *firms do not pay for the additional housing costs* associated to home-based activities. *However, they now consider $S_f' = S_f + \varepsilon L_j$ as a land input* in their production function (Appendix 1).

³ Keeping in mind that we set: $L_i=1$ and $Z_j=1$.

Similarly, *each household must now pay for a total housing cost for a surface area equal to $S_h' = S_h + \varepsilon$* , where ε is the additional housing surface area required to perform home-based activities, as introduced by eq. (2) ($\varepsilon > 0$). The household budget constraint is represented by (3.2). As specified in Subsection 3.1, we assume that *each household maximizes utility on this new total value $S_h' = S_h + \varepsilon$* , even if ε is not fully available for domestic or leisure activities.

In this first scenario (S_1), the equilibria in the composite good and labor markets are not modified compared to the reference case (S_0). They are still represented by (8.1) and (8.2). On the other hand, the condition (10.2) evolves to (12.2) to incorporate the additional housing surface areas ε required by households for home-based activities, while (10.1) remains unchanged:

$$MS_f^* = 2b_0 \quad (12.1) = (10.1)$$

$$MS_f^* + N(S_h^* + \varepsilon) = 2b_1 \quad (12.2)$$

In addition, the space occupied in the residential suburb meets a new condition at the equilibrium:

$$\varepsilon N = M\varepsilon L_j^* \quad (12.3)$$

The total additional housing surface areas occupied by the N households are equal to the total additional areas required by the M firms for production purposes; we thus find the simple relation (8.2) which gives the equilibrium quantity of work required by any firm.

The equilibrium bid-rent function of any household i at any location $x \in [b_0, b_1]$ now depends on the share of home-based activities λ and the additional housing surface area ε :

$$\psi_i^*(x) = \frac{w - 2(1-\lambda)cx - Z_i}{S_h^* + \varepsilon} \quad (3.2b)$$

The monocentric model with additional housing costs paid by households is solved as for the reference case. We obtain the following equilibrium values:

$$S_f^* = \frac{\beta N}{\alpha M} \left(1 - \frac{\alpha}{\beta} \varepsilon\right) \quad \text{iff } \frac{\alpha}{\beta} \varepsilon \leq 1 \quad (13.1)$$

$$S_h^* = \frac{\gamma(\alpha w - \beta c N(1-\lambda)) - \alpha \varepsilon(\delta + \gamma R_a)}{\alpha(\delta + \gamma(c N(1-\lambda) + R_a))} \quad (13.2)$$

$$b_0 = \frac{\beta N}{2\alpha} \left(1 - \frac{\alpha}{\beta} \varepsilon\right) \quad \text{iff } \frac{\alpha}{\beta} \varepsilon \leq 1 \quad (13.3)$$

$$b_1 = \frac{N(\beta(\delta + \gamma R_a)(1 - \frac{\alpha}{\beta} \varepsilon) + \alpha \gamma w)}{2\alpha(\delta + \gamma(c N(1-\lambda) + R_a))} \quad (13.4)$$

The value of the unitary land price R can be written. As expected, the equilibrium value of land consumption by households S_h^* is negatively associated with the size of the additional surface areas required for home-based activities ε . As the household must now pay for the additional surfaces areas, the trade-off is less favorable, all else being equal, to the reference housing surface area S_h^* . The influence of the share of home-based activities λ on the value of S_h^* is not trivial; S_h^* may be negatively associated with λ the following condition on the wage rate:

$$w < \frac{(\alpha \varepsilon - \beta)(\delta + \gamma R_a)}{\alpha \gamma} \quad (14)$$

Proposition 1: *In a standard urban economics monocentric model with a WFH arrangement where the households pay for the additional housing costs, **the equilibrium housing surface area** may negatively depends on the share of home-base activities, on the condition that the wage rate is low enough compared to the agricultural land rent. Numerical application is required.*

In this first scenario, there are two opposing effects. On the one hand, the household budget constraint is relieved by the periods of home-based activities when s.he does not pay the commuting costs. On the other hand, s.he must now pay for the additional surface areas required for home-based activities. According to (9.3), the agricultural land rent sets the city boundary. If R_a is not high enough relative to the wage rate constituting the household's income, the first effect outweighs the second, and the household can acquire larger housing surface areas further from the city center at a lower price.

As expected, the land consumption by the M firms S_f^* is lesser compared with the reference case (without WFH arrangements), as additional surface areas are now provided at the “home office”. For comparable reasons, the number of firms being fixed, the equilibrium value of the CBD limit b_0 is negatively affected compared with the reference case as well. b_0 still evolves positively with the population N if $\frac{\alpha}{\beta} < 1$ and negatively with the total number of firms M . b_0 also evolves negatively with the additional housing surface area ε , as the total $N \cdot \varepsilon$ surface areas used as land inputs in the production function are located outside the CBD.

Last, the equilibrium value of the city boundary b_1 evolves positively with respect to w , and negatively with respect to ε , unconditional. It evolves negatively with N , R_a , c and λ under condition (14).

Proposition 2: *In a standard monocentric model with a WFH arrangement where the households pay for the additional housing costs, the city boundary may negatively depend on the share of home-base activities, on the condition that the wage rate is low enough compared to the agricultural land rent. Numerical application is required.*

The condition (14) to be fulfilled is unchanged. If the agricultural land rent is too low, the lower housing surface areas occupied within the CBD by the same number of firms is more than compensated: (1) by the sum of the additional housing surface areas required for home-based activities; and (2) by the larger reference housing surface areas acquired further from the city center by households. Failure to comply with condition (14) would thus lead to additional urban sprawl.

4.3. Scenario 2: equilibrium of the model with home-based activities: additional housing costs entirely paid by firms

The second scenario (S_2) assumes that firms pay for the full housing costs associated with the additional surface areas required to perform home-based activities (unlike in S_1 where this burden fell on households). This assumption modifies the household budget constraint favorably and the firm's profit function unfavorably compared to S_1 (see Appendix 1). The household budget constraint reverts to that of the reference case (without WFH), with the housing costs now limited to the initial surface area S_h .

$$w L_i - 2(1 - \lambda)cx = p Z_i + R(x)S_h \quad (3.1b)$$

On the other hand, the household still maximizes its utility considering $S'_h > S_h$. The firm's profit function now depends on the additional housing costs as follows:

$$\pi_j(y) = Z_j - w L_j - R_y[S_f + \varepsilon L_j] \quad \forall j \in [1, M] \quad (6b)$$

Where: $S_f + \varepsilon L_j = S'_f$ (5)

Compared with S_1 , the surface area considered as the land input in the production function is still S'_f (Appendix 1). On the other hand, the equilibrium conditions posed by the total surface areas occupied within the CBD and in the entire city remain defined by (10.1) and (10.2).

Solving the monocentric model in S_2 yields the following new equilibrium values:

$$S_f^* = \frac{\beta N}{\alpha M} \left(1 - \frac{\alpha}{\beta} \varepsilon\right) \quad \text{iff } \frac{\alpha}{\beta} \varepsilon \leq 1 \quad (15.1) = (13.1)$$

$$S_h^* = \frac{\gamma(\alpha w - \beta c N(1 - \lambda)) - \alpha \delta \varepsilon}{\alpha(\delta + \gamma(c N(1 - \lambda) + R_a))} \quad (15.2)$$

$$b_0 = \frac{\beta N}{2\alpha} \left(1 - \frac{\alpha}{\beta} \varepsilon\right) \quad \text{iff } \frac{\alpha}{\beta} \varepsilon \leq 1 \quad (15.3) = (13.3)$$

$$b_1 = \frac{N(\beta(\delta + \gamma R_a) + \alpha \gamma w - \alpha \delta \varepsilon)}{2\alpha(\delta + \gamma(c N(1 - \lambda) + R_a))} \quad (15.4)$$

Concerning the surface areas, the equilibrium value of the land occupied by firms S_f^* is not modified compared to S_1 . Concerning households, we verify that the equilibrium value of S_h in this scenario is systematically higher than that obtained in S_1 . This was an expected result, as households do not pay for the additional housing surface areas ε any longer. The CBD limit b_0 remains unchanged compared to S_1 , as the same number of firms M occupy the same amount of land S_f^* at the equilibrium.

Last, we calculate the difference between the equilibrium city boundaries b_1 obtained respectively in S_2 and S_1 . We verify that such difference is positive, unconditional.

Proposition 3: *In a standard urban economics monocentric model with a WFH arrangement where the firms pay for the full additional cost of housing surface areas, the city size is affected upward compared with the case where households pay for the additional housing costs.*

Such a result is due to the highest reference housing surface areas consumed by households, as their budget constraint is relaxed both by the presence of WFH (that allows commuting costs' savings) and, in this scenario, by the assumption of additional housing surface areas being not supported by them. Moreover, the size of CBD is unchanged compared to the previous scenario.

The value of the equilibrium unitary land R price can be written.

4.4. Scenario 3: equilibrium of the model with home-based activities: additional housing costs partially paid by firms

In this third and last scenario (S_3), we assume that firms pay only for the part of the additional housing costs associated with the time where home-based activities are performed. Compared to S_2 , this assumption changes the household budget constraint as well as the firm's profit function (see Appendix 1). However, it does not affect the production function: firms still consider as a land input the entire surface area $S_f + \varepsilon L_j$ (Appendix 1). Because s.he now pays for the additional housing surface area not paid by the firm, the household budget constraint is affected negatively compared to S_2 such that:

$$w - 2(1 - \lambda)cx = Z_i + R(x)[S_h + (1 - \lambda)\varepsilon] \quad (3.1c)$$

On the other hand, utility is still maximized on the total surface area S'_h such that $S'_h = S_h + \varepsilon$.

Unlike the household, the firm's profit function is affected positively compared to S_2 . It now depends on the share of additional housing costs corresponding to telecommuting hours only:

$$\pi_j(y) = Z_j - w L_j - R_y[S_f + \lambda \varepsilon L_j] \quad \forall j \in [1, M] \quad (6c)$$

As in the previous scenarios, we determine the following equilibrium values:

$$S_f^* = \frac{\beta N}{\alpha M} \left(1 - \frac{\alpha}{\beta} \varepsilon\right) \quad \text{iff } \frac{\alpha}{\beta} \varepsilon \leq 1 \quad (16.1) = (13.1)$$

$$S_h^* = \frac{\gamma(\alpha w - \beta c N(1-\lambda) - \alpha \varepsilon(1-\lambda)R_a) - \alpha \delta \varepsilon}{\alpha(\delta + \gamma(cN(1-\lambda) + R_a))} \quad (16.2)$$

$$b_0 = \frac{\beta N}{2\alpha} \left(1 - \frac{\alpha}{\beta} \varepsilon\right) \quad \text{iff } \frac{\alpha}{\beta} \varepsilon \leq 1 \quad (16.3) = (13.3)$$

$$b_1 = \frac{N(\beta(\delta + \gamma R_a) + \alpha \gamma(\varepsilon(\lambda-1)R_a + w) - \alpha \delta \varepsilon)}{2\alpha(\delta + \gamma(cN(1-\lambda) + R_a))} \quad (16.4)$$

We calculated the difference of the equilibrium values of S_h^* : we verified, as expected, that S_h^* is systematically *lower* in this scenario than in S_2 , where the firms paid entirely for the additional housing costs. The equilibrium value of the land occupied by firms S_f^* and the CBD limit b_0 are unchanged compared to S_2 . Last, we verify that the equilibrium value of the city boundary b_1 is now lower than in S_2 , unconditional.

Proposition 4: *In a standard urban economics monocentric model with a WFH arrangement where the firms partially pay for the additional cost of housing surface areas, the size of the city is **lower** than the second scenario (full payment by firms) but higher than the first one (full payment by households).*

As they now pay for the share of additional surface areas not devoted to telecommuting hours, households bear a somewhat stronger budget constraint than in S_2 . We verify that the equilibrium surface areas consumed by households are systematically lesser in the latter scenario than in S_2 . As the size of the CBD remains unchanged compared to the previous scenario, the size of the city is affected downwards.

5. Discussion and Conclusion

In the previous section, we highlighted that the first scenario was the most favorable of the three to urban sprawl containment. In this last section, we discuss the conditions under which such containment could even be better in this scenario (with WFH) than in the reference case.

5.1. Is better containment of urban sprawl compatible with WFH arrangements?

The analytical formulations obtained for the explained variables S_f^* , S_h^* , b_0 and b_1 in the reference case and the three scenarios S_1 , S_2 and S_3 are summarized in Appendix 2.

In this Discussion part, we intend to examine the possibility of a better urban sprawl containment in the presence of WFH arrangements compared to the reference case. To do so, we simply calculate the difference of the equilibrium values of the city boundaries between S_1 (which showed the lowest equilibrium value of the three scenarios for b_1) and S_0 . Having obtained this differential value, we then draw a condition upon the wage rate such that:

$$w > \frac{(\delta + \gamma R_a)(\alpha \varepsilon (\delta + \gamma (cN + R_a)) - \beta \gamma \lambda cN)}{\alpha \gamma^2 \lambda cN} \quad (17)$$

Combining WFH arrangements and a better containment of urban sprawl is possible in the theoretical model at the preceding condition. In the next step, numerical applications will be required to calibrate the monocentric model and verify the realistic feature of the latter condition regarding especially ranges of values for c and N . Moreover, this condition must simultaneously hold with the conditions predictably established by the model, especially condition (14) such that:

$$\frac{(\delta + \gamma R_a)(\alpha \varepsilon (\delta + \gamma (cN + R_a)) - \beta \gamma \lambda cN)}{\alpha \gamma^2 \lambda cN} < w < \frac{(\alpha \varepsilon - \beta)(\delta + \gamma R_a)}{\alpha \gamma} \quad (18)$$

With the additional condition necessary for having positive values of S_f^* and b_0 in any of the three scenarios: $\frac{\alpha}{\beta} \varepsilon \leq 1$.

Highlighting a range of values for w fulfilling these conditions would then be valuable for policy makers in various sizes of cities when considering discussing with firms, given the actual wage rates, about the opportunity to contract WFH arrangement with working households. Alternatively, the conditions for a better urban sprawl containment could be based on threshold values of the unitary travel cost c in order to consider population and/or wage rate levels for which the implementation of a road pricing-type public policy could be compatible with a better containment of urban sprawl. However, the non-linear

form of the expression of c derived from the values of city boundaries in S_0 and S_1 requires again the use of numerical applications.

5.2. Concluding remarks

In this theoretical paper, we emphasized two main results: first, a better urban sprawl containment is achieved in the case of households paying for the additional housing surface areas required to perform home-based activities, compared to the case where firms partially or totally pay for these additional costs; second, urban sprawl containment may even be better achieved on the more favorable scenario compared with the reference case (without WFH arrangements) at a specific double condition that must be fulfilled by the wage rate. A numerical application should confirm the realistic nature of this statement.

Beyond numerical applications, further adjustments of the analytical framework should be provided. From a theoretical point of view, integrating agglomeration economies in the monocentric model would provide a finer representation of the firms' bid-rent function within the CBD. From an empirical point of view, a more realistic representation would be achieved by allocating high-skilled workers a share of home-based activities, but not low-skilled workers (Davis et al., 2021); or, alternatively, by considering two income classes among working households. A second empirical adjustment would be to assume different productivity levels at the workplace and at home resulting in two distinct wage rates for homogeneous employees. This is left for future research.

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Appendices

Appendix 1. Implications of the assumptions of WFH arrangements for the four scenarios on the agents' behavior

Table A.1. Implications of the assumptions of WFH arrangements for the four scenarios on the economic agents' behavior

	S₀. Reference case (without WFH)	S₁. WFH/ Housing surface areas paid by households	S₂. WFH/ Housing surface areas entirely paid by firms	S₃. WFH/ Housing surface areas partially paid by firms
Share of home-based activities	$\lambda = 0$	$0 < \lambda < 1$	$0 < \lambda < 1$	$0 < \lambda < 1$
Household utility	S_h	$S_h' = S_h + \varepsilon$	$S_h' = S_h + \varepsilon$	$S_h' = S_h + \varepsilon$
Household budget constraint	S_h	$S_h' = S_h + \varepsilon$	S_h	$S_h + (1 - \lambda)\varepsilon$
Firm's production function	S_f	$S_f' = S_f + \varepsilon L_j$	$S_f' = S_f + \varepsilon L_j$	$S_f' = S_f + \varepsilon L_j$
Firm's profit	S_f	S_f	$S_f' = S_f + \varepsilon L_j$	$S_h + \lambda \varepsilon L_j$
Spatial footprint of the CBD	$M * S_f$	$M * S_f$	$M * S_f$	$M * S_f$
Spatial footprint of the city	$M * S_f + N * S_h$	$M * S_f + N * (S_h + \varepsilon)$	$M * S_f + N * (S_h + \varepsilon)$	$M * S_f + N * (S_h + \varepsilon)$

Source: Author

Appendix 2. Analytical formulations obtained in the four scenarios

Table A.2. Summary of the analytical formulations obtained for the explained variables in the four scenarios

Variable	S ₀ . Reference case (without WFH)	S ₁ . WFH/ Housing surface areas paid by households	S ₂ . WFH/ Housing surface areas entirely paid by firms	S ₃ . WFH/ Housing surface areas partially paid by firms
S_h	$S_h^* = \frac{\gamma(\alpha w - \beta cN)}{\alpha(\delta + \gamma cN + R_a)}$	$S_h^* = \frac{\gamma(\alpha w - \beta cN(1 - \lambda)) - \alpha\varepsilon(\delta + \gamma R_a)}{\alpha(\delta + \gamma cN(1 - \lambda) + R_a)}$	$S_h^* = \frac{\gamma(\alpha w - \beta cN(1 - \lambda)) - \alpha\delta\varepsilon}{\alpha(\delta + \gamma cN(1 - \lambda) + R_a)}$	$S_h^* = \frac{\gamma(\alpha w - \beta cN(1 - \lambda) - \alpha\varepsilon(1 - \lambda)R_a) - \alpha\delta\varepsilon}{\alpha(\delta + \gamma cN(1 - \lambda) + R_a)}$
S_f	$S_f^* = \frac{\beta N}{\alpha M}$	$S_f^* = \frac{\beta N}{\alpha M} \left(1 - \frac{\alpha}{\beta} \varepsilon\right)$	$S_f^* = \frac{\beta N}{\alpha M} \left(1 - \frac{\alpha}{\beta} \varepsilon\right)$	$S_f^* = \frac{\beta N}{\alpha M} \left(1 - \frac{\alpha}{\beta} \varepsilon\right)$
b_0	$b_0 = \frac{\beta N}{2\alpha}$	$b_0 = \frac{\beta N}{2\alpha} \left(1 - \frac{\alpha}{\beta} \varepsilon\right)$	$b_0 = \frac{\beta N}{2\alpha} \left(1 - \frac{\alpha}{\beta} \varepsilon\right)$	$b_0 = \frac{\beta N}{2\alpha} \left(1 - \frac{\alpha}{\beta} \varepsilon\right)$
b_1	$b_1 = \frac{N(\beta(\delta + \gamma R_a) + \alpha\gamma w)}{2\alpha(\delta + \gamma cN + R_a)}$	$b_1 = \frac{N(\beta(\delta + \gamma R_a)(1 - \frac{\alpha}{\beta} \varepsilon) + \alpha\gamma w)}{2\alpha(\delta + \gamma cN(1 - \lambda) + R_a)}$	$b_1 = \frac{N(\beta(\delta + \gamma R_a) + \alpha\gamma w - \alpha\delta\varepsilon)}{2\alpha(\delta + \gamma cN(1 - \lambda) + R_a)}$	$b_1 = \frac{N(\beta(\delta + \gamma R_a) + \alpha\gamma(\varepsilon(\lambda - 1)R_a + w) - \alpha\delta\varepsilon)}{2\alpha(\delta + \gamma cN(1 - \lambda) + R_a)}$

Source: Author

