Urban Sprawl and Policy Responses: A General Equilibrium Analysis of Residential Choice

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ABSTRACT: This paper examines the driving forces for residential location choice of households in an urban area. It describes a two-region computable general equilibrium model of the core-periphery type (Krugman, 1991), in which residents are mobile between an urban core and its hinterland. We extend these models to integrate interregional housing market interactions and local environmental quality effects, thereby opening up for an analysis of the choice of residence and commuting. Both real income and environmental quality are endogenous variables determining the long run allocation of economic activities across the two regions. In the empirical part of the paper, we solve the model for an urban centre and its hinterland, which are symmetric except for environmental quality. In addition to this baseline, we construct an urban sprawl scenario as a reference scenario to investigate the consequences of two policy instruments. A congestion charge and a spatial planning instrument are implemented to internalize the negative environmental consequences of urban sprawl (relative to the baseline level). Simulation results explain the need for a spatial restructuring of urban areas in order to change transport related pollution. We find that both instruments generally reduce urban sprawl, though they do so through different channels (change in the share of commuters and non-commuters). Regarding environmental impacts, both policies lead to desirable effects for the overall region, yet with different effects for ambient levels of pollution per region.

JEL: D58, Q53, R14, R23, R41

KEYWORDS: urban sprawl, commuting, environmental quality, geographical economics, CGE modelling.

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1. Introduction

While transport services are crucial to economic activities, the transport sector in its current shape is connected to a range of detrimental impacts. Mobility activities currently trigger the fastest increasing segment in fossil fuel emissions. Demands for transport reorganisation also arise from current noise and health impacts in urban areas. In particular, nowadays urban regions are facing the problem of (re)location of residents and jobs and the amount of traffic generated by commuting activities. This results in, for example, high ambient levels of particulate matter in urban cores which give an additional incentive for climate relevant transport improvements.

Transport flows are crucially interlinked with economic activity levels in the production and household sectors. This mutual linkage is a clear conclusion from the now advanced New Economic Geography (NEG) literature, mainly drawing on theoretical and stylised models so far (for a comprehensive survey see Fujita et al., 1999; Baldwin et al., 2003). In particular, transportation interacts with urban development via real income effects, housing demand and mode choice. The accessibility of jobs and services has an important impact on the residential choice behaviour of households. In addition, the household choice is influenced by the existence of local environmental amenities and space. The trade-off between these driving factors determines the equilibrium structure of the urban residential distribution.

The aim of this paper is to gain insight into the driving forces in residential location choice behaviour and the population dynamics of an urban region in the long term. We investigate the way in which the moving behaviour of residents interacts with the characteristics of residential locations (such as local environmental quality and housing prices) and with commuting activities. The particular issue we address is urban sprawl and pollution triggered by passenger transport.

Moreover, we seek to enhance the modelling of environmentally relevant transport demand. We do so by developing a two-region model building on (i) the theoretical NEG modelling advances and (ii) the spatially explicit extension of transport oriented economic computable general equilibrium (CGE) analysis. Hereby, the levels of real income and environmental quality are endogenous variables determining the long run allocation of economic activities across the two regions. In the proposed model, this allocation is expressed by λ, the equilibrium outcome of the population distribution across regions. Thus, by solving for λ the model examines the distribution of residences and workplaces and the shift in the share of cross-regional commuters.

In the empirical part of the paper, we set up a stylized centre-hinterland model where both regions are perfectly identical except for environmental quality. We

then proceed to evaluate policy measures, with a focus on economic instruments for emission reduction and on spatial restructuring measures.

This paper is structured as follows. Section 2 reports on the theoretical model including a literature review, while the existence and stability of equilibria is discussed in Section 3. In Section 4 the theoretical model is implemented in a CGE format. Section 5 deals with the implementation of two policy measures, a congestion charge and a spatial planning instrument, into the CGE model. Then we outline the effects of these policies on urban residential distribution and commuting flows, on environmental quality and utility levels. Section 6 summarizes the results and concludes.

2. The theoretical model

2.1. An overview of New Economic Geography models

This section presents an overview of existing two-region models which are based in New Economic Geography (NEG). The majority of them are extensions of the canonical core-periphery (CP) model (Krugman, 1991; Fujita et al., 1999; Baldwin et al., 2003), others start from the standard monocentric-city model (Alonso, 1964). In particular the CP modelling approach of Krugman has been modified along several lines (Ottaviano and Puga, 1998; Eckey and Kosfeld, 2004; Fujita and Mori, 2005).

The standard CP model contains the analytical essence of the NEG. It shows how the interactions between transport costs, increasing returns at firm level and factor mobility endogenously determine the extent of regional specialisation through simultaneous location choices of firms and labour. Hereby, the emphasis is on the firm's location decision. A second important point is that the CP model focuses on the alteration of transport costs to explain agglomeration patterns. However, in order to understand regional differences in population density, additional forces such as housing scarcity or urban pollution problems are to be included.

The consideration of non-tradable services in the NEG goes back to Helpman (1998), who replaces the standard agricultural sector with housing services. Residents are mobile, but they live and work in the same place. While in the standard NEG model dispersion is driven by region-specific demands by farmers, who own the homogenous product, in this model it is region-specific supplies (of homogenous housing) that act as a dispersions force. Helpman finds that agglomeration is more likely to occur when (interregional) transport costs are higher, which contradicts Krugman's result that falling transport costs lead to regional divergence.

All three sectors (agriculture, manufacturing, housing) are taken into consideration by Suedekum (2006) and Pflueger and Suedekum (2006). Suedekum's (2006) model implies that the true costs of living may be higher in the centre region,

contradicting standard CP model predicitions. He builds on the integration of housing scarcity as a main determinant of regional price differentials. By contrast, Pflueger and Suedekum (2006) investigate the welfare effects of agglomeration and efficiency arguments for policy invention. Their main contribution is in finding an analytically precise way to disentangle the net pecuniary externality with mobile firms in the monopolistically competitive sector. What these two papers share, however, is the assumption of housing as a non-traded and non-produced consumption good (as in Helpman, 1998). As a result, there is no differentiation between the place of work and residence.

A number of papers (e.g. Tabuchi, 1998; Murata and Thisse, 2005) add urban structures to the NEG such that households face a trade-off between transport costs for space and amenity. Thereby, Murata and Thisse (2005) aim to unify the work of Helpman (1998) and Tabuchi (1998). The regional specification of these models is based on the monocentric residential model (Alonso, 1964), where workers live around a central business district and commute to it. With two regions of this type, these models do allow for the interplay between interregional commodities' transport costs and urban costs, i.e. workers' intraregional commuting costs and housing costs, in a spatial economy. Yet, by this means, they abstract from interregional commuting. A similar approach is developed by Tabuchi and Thisse (2006), who use the model developed by Ottaviano et al. (2002) (as an alternative to Krugman's (1991) set up) and who then extend their basic model to two sectors to study regional specialisation and urban hierarchy.

Regarding environmental concerns, Quaas and Lange (2007) extend the canonical CP model to include local environmental pollution, which is linked to production and thus to a concentration of skilled labour. Urban environmental problems act as a spreading force, because they make agglomerations less favourable (producer-consumer externalities). In comparison to Krugman's results, their model can explain a third and more realistic type of equilibrium, i.e. a stable asymmetric and incomplete agglomeration of skilled workers in one of the two regions. Note that the occurring externalities in Quaas and Lange are of the producer-consumer type typically found in environmentally oriented models (see also e.g. Verhoef and Nijkamp, 2002; Arnott et al., 2004; Marrewijk, 2005; Yoshino, 2004). By contrast, an urban general equilibrium model with pollution from commuting was developed by Verhoef & Nijkamp (2003), yet this was accomplished in a monocentric city setup.

Eppink and Withagen (2006) extend Krugman's CP model by the local level of biodiversity which is a function of two types of species with different extinction risks. As in Quaas and Lange (2007) the extension happens in an additive-separable form.

Drawing on these lines of work, we propose a simple model of economic geography to analyse the main determinants of urban sprawl and to address efficiency arguments for policy intervention.

2.2. The basic model set-up

We model an economy consisting of two regions, an urban core and its hinterland (*), which we will distinguish by an asterisk. The framework is based on various modifications of Krugman's (1991) core-periphery (CP) model, whereby two extensions are particularly important: (i) the incorporation of urban features (housing market, commuting) into the NEG framework (Helpman, 1998; Tabuchi, 1998; Murata and Thisse, 2005; Tabuchi and Thisse, 2006), and (ii) the consideration of environmental aspects within a NEG framework (Yoshino, 2004; Quaas and Lange, 2007). More specifically, approaching from one side we extend Suedekum's (2006) framework by environmental quality, thereby following Quaas and Lange (2007) and Eppink and Withagen (2006). Contrary to typical environmentally-oriented models (e.g. Marrewijk, 2005; Yoshino, 2004; Quaas and Lange, 2007) that handle producer-consumer externalities we assume pollution to be caused by commuting residents only, i.e. the intensity of mobility trends (expressed by the dimension of urban sprawl) is affecting the level of environmental quality. Approaching from the other side, we introduce a housing market into the model by Quaas and Lange (2007), thereby following Suedekum (2006). An additional extension is that we let housing to be traded at a cost in order to model interregional commuting. Hence, while in the CP model agglomeration is slowed down only by transport costs, we integrate other forces such as varying property prices and negative environmental impacts due to unfavourable mobility behaviour. This implies a more realistic assumption of re-dispersion of economic activity. While the NEG has dealt mainly with firms' location of production, the present paper thus focuses on consumers' decisions to understand regional differences in population density.

In this endeavour, we assume that mobile consumers choose either of the two regions to live and work depending on what benefit the location offers in terms of environmental quality, housing and variety in consumption goods. Residents purchase differentiated products in both regions, whereby "imported" goods are costly to transport. In addition, residents pay commuting costs if the location of residence differs from the place of work.

The economy comprises two sectors of production. First, a variety of manufacturing goods is produced under internal increasing returns to scale by labour and capital in a monopolistically competitive market. Second, the housing sector operates under perfect competition by use of labour so that $p_H = w_H$ and $p_H^* = w_H^*$. Capital is equally owned by all manufacturing workers. There are three (sector-specific) factors of production: While labour used in the housing production L_H is immobile and equally distributed between core and hinterland, manufacturing workers L_M are interregionally mobile, thereby determining a specific settlement structure. Moreover, capital K_M is freely mobile across regions. We choose units for the supply of manufacturing workers $\overline{L}_M = L_M + L_M^* = \alpha$ and for housing producers $L_H = L_H^* = (1-\alpha)/2$, which yields $\overline{L}_H = 1-\alpha$.

Consequently, the supply of housing in each region is fixed at $\overline{H}_c = \overline{H}_h = (1-\alpha)/2$. In addition, $L = L_M + L_H$ and $\overline{L} = \overline{L}_M + \overline{L}_H = 1$, and total capital supply is $\overline{K}_M = K_M + K_M^* = 1$.

2.3. Consumption

We assume that local environmental quality Q is an essential component of consumers' welfare. Its level depends on the environmental impact of the number of commuters and non-commuters in each region. The share of commuters in the workforce per region is given by s and s^*. The according damage function $D(s)$, $D(s) \leq 0$, will be described below. For the moment, let $D(s)$ affect the level of environmental quality as follows, implying a decrease in environmental quality with rising damage:

$$Q = e^{D(s)} \text{ and } Q^* = e^{D(s^*)} \tag{1}$$

All workers are final consumers and share the same preferences on Q, the composite manufacturing good M and housing H. While Q enters the utility function directly in an additively separable form

$$U(M,H,Q) = M^{\alpha}\left(H_c^{\beta} H_h^{1-\beta}\right)^{1-\alpha} + \delta Q \qquad 0 \leq \alpha \leq 1;\ 0 < \beta < 1,\ \beta \neq 0.5 \tag{2}$$

The notation is for the centre region with expressions identical for the hinterland. Parameter β indicates the preference for commuting, with $\beta = 1$ indicating full aversion to commuting. Parameter $\delta \geq 0$ expresses the intensity of environmental preferences. To model how utility increases via consumers' love for variety, following Dixit and Stiglitz (1977), let the composite M be a subutility CES function defined over a range of varieties $i \in \left]0; \hat{n}\right]$ and let $\sigma \equiv 1/(1-\rho)$ indicate the constant elasticity of substitution in preferences between any pair of varieties

$$M = [n(m(i))^{\rho} + n^*(m(j)^*)^{\rho}]^{\frac{1}{\rho}} \qquad 0 < \rho < 1 \tag{3}$$

with the consumption of each local variety denoted by $m(i)$ and of each "imported" variety by $m(j)^*$. Centre varieties n belong to the interval $\left]0; n\right]$; hinterland varieties n^* belong to the interval $\left]n; \hat{n}\right]$. The representative household maximises (2) subject to (3) and to the budget constraint (4), where Y is total regional income, p_M the price of variety i and p_H the price of housing:

$$Y = p_H H_c + R\, p_H^* H_h + G \cdot M \quad \text{where } G \cdot M = [n p_M m(i) + n^* p_M^* m(j)^*] \tag{4}$$

Equation (4) captures the price p_H for housing in the home region H_c and the price of the neighbour region including commuting costs, $p_H^* R$, with $R \geq 1$, for demand in the alternative region H_h. Index G denotes the price index of the manufacturing composite[2] M as given in equation (3). See equation (5) for a specification of G, where parameter T models passenger transport costs in consumption. These transport costs are assumed to be of the iceberg form introduced by von Thünen (1826) and Samuelson (1952), i.e. only a fraction $1/T$ of the transported good arrives in the other region. In other words, for each unit delivered T units have to be shipped. In the present model, transport costs are incurred whenever residents decide to buy *not* in the local market but to purchase in the other region.

$$G = [n\,(p_M)^{1-\sigma} + n^*(p_M^* T)^{1-\sigma}]^{1/(1-\sigma)} \qquad T \geq 1 \tag{5}$$

By use of the same technology, the producer price p_M is identical for all firms within a region, i.e. with p_m as the consumer price, $p_m(i) = p_M$ and $p_m^*(i) = p_M^*$ for all varieties i.[3] Utility maximisation yields the demand for consumption varieties and for housing. The demand for local and imported varieties is

$$m(i) = \alpha\, Y \frac{p_M^{\;-\sigma}}{G^{1-\sigma}} \text{ and } m(j)^* = \alpha\, Y \frac{(p_M^*\, T)^{-\sigma}}{G^{1-\sigma}} \tag{6}$$

such that the demand for manufactures produced in the centre, made up of its own demand and the demand of the hinterland, including goods to be shipped, adds up to

$$m(i) + m(i)^* = \alpha\left[Y(p_M)^{-\sigma} G^{\sigma-1} + Y^*(p_M)^{-\sigma} T^{1-\sigma} (G^*)^{\sigma-1}\right] \tag{7}$$

The housing demand by labour force per region H is composed of demand from residents living on site (non-commuters) and from residents commuting from outside, i.e. $H = H_c + H_h$. While non-commuters demand housing in the region they work in, where demand is H_c for the centre population and H_h^* for the hinterland, residents who commute cross-regionally face higher housing prices due to commuting costs R and thus demand H_h and H_c^*. Hence, housing demand for each workforce can be written as (where the subscript refers to the place of residence, i.e. c for centre and h for hinterland, and the superscript for the place of work, i.e. an asterisk refers to the hinterland):

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[2] The price index is defined such that G times M is equal to expenditure: $\int_0^{\hat{n}} p_m(i)\, m(i)\, di = G \cdot M$, where $G = \left[\int_0^{\hat{n}} p_m(i)^{1-\sigma}\, di\right]^{1/(1-\sigma)}$ and $M = \left[\int_0^{\hat{n}} m(i)^{\rho}\, di\right]^{1/\rho}$.

[3] By assuming the same price for all varieties, for the case of costless transportation, G (as defined in footnote 1), becomes $G = p_M \cdot \hat{n}^{1/(1-\sigma)}$.

$$H = H_c + H_h \qquad \text{for the centre}$$
$$H^* = H_c^* + H_h^* \qquad \text{for the hinterland} \qquad (8)$$

where the demand for commuters and non-commuters are as follows (with β defined as in equation (2)):

$$H_c = (1-\alpha)\beta \frac{Y}{p_H}, H_h^* = (1-\alpha)\beta \frac{Y^*}{p_H^*} \qquad \text{for non-commuters}$$
$$H_c^* = (1-\alpha)(1-\beta)\frac{Y^*}{p_H R}, H_h = (1-\alpha)(1-\beta)\frac{Y}{p_H^* R} \qquad \text{for commuters} \qquad (9)$$

2.4. Housing

As workers can migrate to the other region, but housing production is fixed in quantitative terms (not in terms of prices), oversupply in one region and undersupply in the other will occur. The arising changes in housing prices induce a fraction of the population in the more densely populated region to look for housing in the other region.

The supply of housing goods in each region is fixed at $\bar{H}_c = \bar{H}_h = (1-\alpha)/2$. The region-specific demand – in contrast to the labour force concept of demand functions in (8) – can be calculated from equations (9) and is composed of home demand and demand from residents who commute to the other region:

$$\tilde{H}_c = H_c + H_c^* \qquad \text{for the centre}$$
$$\tilde{H}_h = H_h^* + H_h \qquad \text{for the hinterland} \qquad (10)$$

The housing concept introduced in equation (10) is essential for market clearing. Set equal to the fixed housing supply, (10) determines the equilibrium housing price. The housing market is cleared by the Armington assumption of product heterogeneity[4], which determines the degree to which the trade balance in housing varies. Thus, the housing demand of commuters H_h and H_c^* or, expressed differently, the "exported" quantities of the housing good, are determined by

$$H_c^* = r_c \bar{H}_c \left(\frac{p_H^*}{p_H R}\right)^{\varepsilon} \text{ and } H_h = r_h \bar{H}_h \left(\frac{p_H}{p_H^* R}\right)^{\varepsilon} \qquad (11)$$

[4] Under the Armington assumption domestic housing goods are treated as qualitatively different from goods imported from the other region.

A change in relative housing prices shifts the trade balance in housing by a certain degree which is given by ε, the Armington elasticity of substitution between home production of housing and imports. This shift corresponds to a shift in the settlement structure which is characterised by the allocation of residences and workplaces. The variables r_c and r_h denote the reference level of housing exports (at reference prices and corresponding income, both denoted by a zero for reference period), based on equations (11):

$$r_c = \frac{H_c^*(p_{H,0}, Y_0^*, R_0)}{\bar{H}_c} \text{ and } r_h = \frac{H_h(p_{H,0}^*, Y_0, R_0)}{\bar{H}_h} \tag{12}$$

2.5. Environment

In order to specify the level of environmental quality, we assume that emissions are solely caused by passenger transport and that differences between the two regions in terms of causing pollution are mainly driven by traveling to work. It is both workers commuting cross-regionally (who we will refer to as "commuters" in the following) and workers whose region of residence coincides with the region they work in ("non-commuters") who contribute to pollution. By differentiating two regions of residence and two types of workers by mobility behaviour, we distinguish four groups of workers: Non-commuters in the centre (group 1), non-commuters in the hinterland (group 2), commuters originating in the centre (commuters to the hinterland) (group 3), and commuters originating in the hinterland (commuters to the centre) (group 4). To model these groups, we first need their share in the labour force per region, with s representing the commuter share in the centre, and $(1-s)$ representing the centre's non-commuters. The shares are defined analogously for the hinterland,

$$s = \frac{H_h}{H},\ (1-s) = \frac{H_c}{H},\ s^* = \frac{H_c^*}{H^*} \text{ and } (1-s^*) = \frac{H_h^*}{H^*}, \tag{13}$$

so that the four groups of workers, g_1, g_2, g_3 and g_4, can be written as

$$g_1 = (1-s)\lambda,\ g_2 = (1-s^*)\lambda,\ g_3 = s^*(1-\lambda) \text{ and } g_4 = s^*(1-\lambda). \tag{14}$$

The variable λ corresponds to the share of the centre labour force in manufacturing of total manufacturing labour across regions, i.e. $\lambda = L_M / \bar{L}_M$, and vice versa for the hinterland share $(1-\lambda)$[5]. To calculate the levels of environmental quality per region, we assume that commuters to the centre (group 4) contribute to the centre level of environmental quality Q and commuters to the hinterland (group 3) contribute to the hinterland level Q^*. Moreover, each type of worker causes

[5] See Section 3 for the derivation of λ.

pollution by a group-specific environmental impact factor, which we denote by μ. Having fixed this, the damage functions $D(s)$ and $D(s^*)$ from equation (1) can be specified as

$$D(s) = -(\mu_c(1-s) + \mu_h s) \text{ and } D(s^*) = -(\mu_h^*(1-s^*) + \mu_c^* s^*) \tag{15}$$

Thus, the representative household splits income Y between M, H_c and H_h. Each variety $m(i)$ and $m(i)^*$ is chosen such that the costs of attaining M as determined in the first step are minimized. Expressing the consumers' maximised utility as a function of income and prices yields the indirect utility function

$$u_M = \omega\,\Omega + \delta Q = y_M G^{-\alpha}\left(p_H^{\beta}(p_H R)^{1-\beta}\right)^{-(1-\alpha)}\Omega + \delta e^{D(s)} \tag{16}$$

where y_M is per capita income in manufacturing and ω its real value, i.e. $\omega = y_M / (G^{\alpha}(p_H^{\beta}(p_H R)^{1-\beta})^{(1-\alpha)})$; $\Omega = \alpha^{\alpha}(1-\alpha)^{1-\alpha}(\beta^{\beta}(1-\beta)^{1-\beta})^{1-\alpha}$ is a constant. The per capita utility, as we will later see, determines the manufacturing workers' location decision, since residents choose the region to settle where their utility is maximised. By this means, the welfare of a worker is given by equation (16) evaluated at equilibrium prices.

2.6. Production

We assume a manufacturing sector producing a heterogeneous consumption good, following Dixit and Stiglitz (1977). Production of all varieties requires labour and capital, and all firms use the same technology. The labour l_M required to produce quantity q_M of any variety i involves fixed labour input F and marginal labour input a_M:

$$l_M = F + a_M q_M \tag{17}$$

Hence, there are increasing returns to scale in the production of each variety. A firm's demand for capital k_M is determined by a constant capital-to-labour ratio $c_M = k_M / l_M$ (see Eppink and Withagen, 2006), which is identical for all firms. Firms earn economic rents by applying mark-up pricing, yet costless entry and exit drive profits to zero. Let w_M be the wage rate, p_M the f.o.b. price and p_K the price of capital. Then, given demand for variety i produced in the centre region (7), each firm producing a specific variety behaves so as to maximize profit $\pi = p_M q_M - (w_M + p_K c_M)(F + a_M q_M)$. The FOC, together with a constant price elasticity of demand, $\varepsilon = \sigma = 1/(1-\rho)$, give the profit-maximising price p_M for each

variety as a fixed mark-up over marginal cost. Including the normalisation[6] $a_M \equiv \rho$, this yields

$$p_M = \frac{a_M(w_M + p_K c_M)}{\rho} = w_M + p_K c_M = y_M \tag{18}$$

so that the profit-maximizing price equals per capita income in manufacturing from labour and capital.

3. Existence and stability of equilibria

3.1. Instantaneous equilibrium

We determine the short-run equilibrium by deriving the equilibrium conditions for the endogenous variables y_M, Y, G and p_H in each region. The according outcome, i.e. an equilibrium for a given distribution λ of manufacturing workers over the two regions, is characterised by optimising behaviour of consumers and firms and by market clearing. Due to the additively-separable form of the utility function (2), the demand functions do not depend on environmental quality *Q*. In the long-run, by contrast, environmental quality does affect the location decision of households.

Recalling that total labour supply $\overline{L}_M = \alpha$ and using the normalisations $a_M \equiv \rho = (\sigma - 1)/\sigma$ and $F \equiv \alpha/\sigma$, in instantaneous equilibrium a firm's labour demand equals its output, i.e. $l_M = q_M = \alpha$, while the demand for capital is $k_M = c_M \alpha$. The labour market and the capital market thus clear. The equilibrium number of firms, which equals the number of varieties produced, is then given by $n = L_M/\alpha = K_M/(c_M \alpha)$. It follows that the number of active firms *n* is equal to the share of manufacturing labour $\lambda = L_M/\overline{L}_M$, $0 < \lambda < 1$, in the respective region, so that $n = \lambda$ and $n^* = 1 - \lambda$.

Moreover, firms attain the equilibrium output if q_M equals total demand for any variety as given in (7), thereby clearing the manufacturing market. This, together with the pricing rule (18) gives us the first pair of equilibrium conditions, i.e. the income of a manufacturing worker at which firms break even (19). Instantaneous equilibrium is characterised by the following 8 equations:

$$\begin{aligned} y_M &= \left[Y G^{\sigma-1} + Y^* T^{1-\sigma} (G^*)^{\sigma-1}\right]^{\frac{1}{\sigma}} \\ y_M^* &= \left[Y^* (G^*)^{\sigma-1} + Y T^{1-\sigma} G^{\sigma-1}\right]^{\frac{1}{\sigma}} \end{aligned} \tag{19}$$

With $n = \lambda = L_M/\alpha$, $p_M = y_M$ and $w_H = p_H$ total income *Y* per region is denoted by

[6] For standard normalizations used throughout the paper see e.g. Fujita et al. (1999).

$$Y = \alpha\,\lambda\, y_M + p_H \frac{(1-\alpha)}{2}$$
$$Y^* = \alpha\,(1-\lambda) y_M^* + p_H^* \frac{(1-\alpha)}{2} \tag{20}$$

and the region specific price indices (as given in equation (5)) can be written as

$$G = \left[\lambda (y_M)^{1-\sigma} + (1-\lambda)(y_M^*\, T)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}$$
$$G^* = \left[\lambda (y_M T)^{1-\sigma} + (1-\lambda)(y_M^*)^{1-\sigma}\right]^{\frac{1}{1-\sigma}} \tag{21}$$

The housing market clears if supply $\bar{H}_c = \bar{H}_h = (1-\alpha)/2$ equals demand, $\tilde{H}_c$ and $\tilde{H}_h$, as given in equations (10). Hence, housing prices are

$$p_H = 2[\beta\, Y + (1-\beta)\frac{Y^*}{R}]$$
$$p_H^* = 2[\beta\, Y^* + (1-\beta)\frac{Y}{R}] \tag{22}$$

3.2. Long-run equilibrium

In this section we analyse what happens to the settlement structure in the long run, in particular we study how adjustment processes result in a specific population split expressed by the value of λ. The driving force in the migration process is the residents' utility differential between the core and the hinterland region. A long-run equilibrium, i.e. a short-run equilibrium in which the allocation of mobile workers λ is also in equilibrium, occurs when no resident may get a higher utility level by changing location. This is the case if per capita utility levels (as given by equation (16)) between core and hinterland are equalised, i.e. $u_M = u_M^*$. We call the according distribution $\lambda \in [0, 1]$ a *spatial equilibrium*, which arises therefore at

$$\begin{array}{lll} 0 < \lambda < 1 & \text{when} & \Delta u_M \equiv u_M(\lambda) - u_M^*(\lambda) = 0 \text{ or at} \\ \lambda = 1 & \text{when} & \Delta u_M(1) \geq 0 \text{ or at} \\ \lambda = 0 & \text{when} & \Delta u_M(0) \leq 0 \end{array} \tag{23}$$

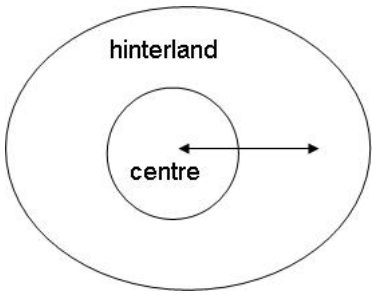
We assume a myopic adjustment process, i.e. workers are attracted by the region that has a higher utility than the average utility (over both regions). A gradual migration process stems from the fact that residents have different moving costs. Migration is thus governed by the ad hoc adjustment dynamics (Fujita et al., 1999)[7]

[7] These dynamics are equivalent to the replicator dynamics used in evolutionary game theory. Hereby, subpopulations that are associated with better-than-average strategies grow, while those

$$\dot{\lambda} = \Delta u_M(\lambda)\lambda(1-\lambda) \Leftrightarrow \dot{\lambda} = \left[(\omega - \omega^*) + \delta(Q - Q^*)\right]\lambda(1-\lambda) \tag{24}$$

Since in the long run no resident has an incentive to relocate, a spatial equilibrium implies $\dot{\lambda} = 0$. If the utility differential Δu_M is positive, there is an incentive for some workers to move from the hinterland to the centre, and vice versa for a negative differential.

Figure 1: Migration between the centre and the hinterland region



The migration dynamics is governed by households who choose the location to settle that offers the higher level of welfare. In this way, the urban residential dynamics is an outcome of all the households' simultaneous individual choices. For the present model, household residential choice depends on differences in real income ω and in environmental quality Q. Residents face two trade-offs which differ in terms of substitutability:

First, workers choose the consumption good and housing at a cost. The utility specification (2) suggests a limited substitutability between M and H, which are imperfect substitutes. Hereby, the price index of manufacturing goods G is sensitive to the number of firms n in each region, i.e. sensitive to the population split λ. Then, a region's price index G falls with the rising size of its population. In the housing sector, a fixed supply of housing per region faces changing demand levels with shifts in λ. Since workers are mobile between the regions, oversupply in one region and undersupply in the other will occur. The arising changes in housing prices induce a fraction of the population to look for housing in the other region; a fraction that is growing as long as the other region has cheaper housing prices net of commuting costs.

Second, households face a trade-off between goods they pay for in monetary terms and environmental quality. The difference to the trade-off between M and H the additive-separability in (2) reflecting that private (M, H) and public goods (Q) are perfect substitutes.

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associated with worse-than-average strategies decline In particular, $\dot{\lambda} \equiv d\lambda/dt = (u_M - \bar{u}_M)\lambda$ with $\bar{u}_M = \lambda u_M + (1-\lambda)u_M^*$ with t being time (e.g. Weibull, 1995).

3.3. Existence and stability conditions

We shall investigate the *existence* of equilibria by means of equations (23) and (24). The most obvious spatial equilibrium arises with equality in real income ω and environmental quality Q across regions. For this equality it can be easily seen that the utility differential is zero. Alternatively, the difference in real income levels may be compensated by the difference in environmental quality (with opposite sign). In particular, the spatial equilibrium is in this case characterised by either $\omega > \omega^*$ and $Q < Q^*$, or $\omega < \omega^*$ and $Q > Q^*$. Thus, for a lower ω (relative to the other region) residents are compensated by a higher Q and vice versa for a relatively low level of Q. With otherwise identical regions such an equilibrium is the consequence of environmental differentiation between the regions.

For the model specified in Section 2, a solution exists for the following combination of parameter values, where the crucial parameters model the housing market: the commuting cost factor R and the preference for commuting β. Thus, for zero commuting costs ($R = 1$), a solution exists only if there is no indifference in the residential choice ($\beta \neq 0.5$), or if there is no full aversion to commuting ($\beta \neq 1$). The two special cases described below will further illustrate these conditions.

A spatial equilibrium is asymptotically *stable* if, for any marginal deviation of the population distribution from the equilibrium, the model dynamics brings the distribution of mobile labour back to the original one.[8] The distribution to be analysed for the model on hand, which is the dispersed configuration with $0 < \lambda < 1$, is stable if and only if the slope of Δu_M is non-positive in a neighbourhood of this point.

In order to derive the stability conditions, let us assume identical regions with respect to the production of manufacturing and housing and also with regard to environmental impacts. Now consider a situation where residents are equally spread between the regions such that $\lambda = ½$. With identical regions this must be an equilibrium since $\omega = \omega^*$ and $Q = Q^*$ and thus $u_M = u_M^*$. By totally differentiating (16) around the symmetric steady state with respect to λ we derive $du_M / d\lambda$, the equilibrium respond, which is the change in per capita utility caused by a movement of residents,

$$\frac{du_M}{d\lambda} = \frac{d\omega}{d\lambda} + \delta \frac{dQ}{d\lambda} \tag{25}$$

[8] In order to study stability of the equilibrium, if some workers migrate to the other region, local markets are assumed to adjust instantaneously. In particular, the number of firms in each region must be such that equation (33) remains valid for the new settlement structure of residents. Then, wages are adjusted such that firms earn zero profits.

For the full notation of (25) and its derivation we refer to the Appendix (A.1). If $du_M/d\lambda$ is negative for the exogenous parameter values of σ, α, δ, μ, T and R, the symmetric case $\lambda = ½$ is a stable equilibrium and vice versa for a positive value. Moreover, the symmetric solution is characterized by identical environmental damage parameters across regions. Then, for the parameter values $\sigma = 5$ and $\alpha = 0.8$ (see Table 1), we find that the symmetric case is a stable equilibrium ($du_M/d\lambda < 0$).

Furthermore we identify to special cases, where solutions do not exist. First, we find the case of complete preference for housing close to the workplace such that there is no commuting ($\beta = 1$) and thus commuting costs R become irrelevant. Second, there is the case of complete indifference in the housing decision together with costless commuting ($R = 1$ and $\beta = 0.5$). For both cases $du_M/d\lambda$ is calculated in the Appendix (equations (A7) and (A8)).
In the first case where $\beta = 1$, the equilibrium outcomes for λ are independent from the introduction of Q in the present model, since $dQ = 0$. Environmental effects are absent due to the specification of environmental quality (see equations (1) and (14)), while changes in the remaining variables ((A2) to (A5) in the Appendix) remain non-zero. However, there is no differentiation between commuters and non-commuters. The location of residence always coincides with the place of work, implying that the model dynamics is not of further interest for us.
By contrast, for the combination of indifference in housing and free commuting, $R = 1$ and $\beta = 0.5$, environmental effects are absent because there is no change in housing prices with different equilibrium outcomes for λ. I.e. $dQ = 0$ because $dp_H = 0$. Workers are completely indifferent between home production of housing and imports ($\beta = 0.5$) and, in addition, do not pay for commuting ($R = 1$).

4. The CGE model

In the present section, we describe the empirical implementation of the theoretical model derived in Section 2 and analysed in Section 3. It is characterized by equations (19), (20), (21) and (22) and used for the analysis of core forces in urban sprawl. Being interested in the equilibria that this system tends to, we need to explore system behaviour under the specification of particular functional forms and parameters. We thus numerically solve this system and therefore apply spatial computable general equilibrium analysis. We apply a two-regional split up of economic data of the NUTS III region Graz (Austria), which consists of the two political districts Graz city and Graz hinterland.

As a baseline scenario, we assume that the two regions are perfectly identical except for environmental effects. In particular, the emission parameters differ between the centre and the hinterland. As a consequence, the equilibrium value of λ and the arising size of the four groups of workers are not symmetric across regions. Secondly, to illustrate urban sprawl in our model, we assume that commuting

across regions is promoted and thus the population in the hinterland increases while the centre population falls. Thirdly, we investigate the consequences of two policy instruments which are implemented in order to internalize the environmental consequences of urban sprawl. Thus, the environmental quality in these policy scenarios is, starting from the sprawl situation, improved towards the baseline level.

4.1. The reference specification and the baseline scenario

As a first step, we will briefly describe the (long-run) equilibrium in the case without policy interventions. This case will serve as a reference case to compare the policy simulations to. Let us first specify exogenous parameters and initial variables as introduced in the theoretical model in order to calibrate the reference equilibrium; the values are given in Table 1 and Table 2. For the description and normalizations of the remaining variables we refer to Appendix A.2.

Table 1: The parameters values

parameter	value	description
$0 \leq \alpha \leq 1$	0.8	expenditure share consumption good (*own calculation for Graz area*)
$1-\alpha$	0.2	expenditure share housing
$0 < \rho < 1$	0.8	intensity of preference for variety (*Eppink and Witthagen, 2006*)
$\sigma = 1/(1-\rho)$	5	elasticity of substitution between varieties (*Eppink and Witthagen, 2006*)
$\delta > 0$	5000	scaling parameter for environmental quality (intensity of environmental preferences)
$\mu_c \geq 0$	0.22	environmental damage parameter for group 1 (*own calculation for Graz area*)
$\mu_h^* \geq 0$	0.44	environmental damage parameter for group 2 (*own calculation*)
$\mu_c^* \geq 0$	0.64	environmental damage parameter for group 3 (*own calculation*)
$\mu_h \geq 0$	0.64	environmental damage parameter for group 4 (*own calculation*)
σ_{MM^*}	1	elasticity of substitution between home production of manufactures and imports (*assumption*)
σ_{HH^*}	0.5	Armington elasticity of substitution between home production of housing and imports (*assumption*)
$U > 0$	1	urban sprawl parameter (initial value)
$R \geq 1$	1	commuting transport cost factor (in the housing market) (initial value)
$T \geq 1$	1	(interregional) iceberg transport cost factor (initial value)
$P > 0$	1	spatial policy parameter in hinterland (initial value)

In manufacturing labour and capital are employed in a Cobb-Douglas production technology. In order to differentiate between the place of work and residence of the manufacturing workers (interregional commuting), we let the housing good be traded, while the workforce in housing remains an immobile factor of production. Cross-regional commuters who work in the centre and live in the hinterland hence "import" the housing good from the peripheral region (and vice versa for imports from the centre). Since the housing production is fixed in quantitative terms in each region yet workers are mobile, the arising changes in housing prices induce a fraction of the population to look for housing in the other region.

Table 2: The exogenous and initial variables

Variables	Value	Description
$\overline{L}_M = L_M + L_M^* = \alpha$	0.8	Manufacturing labour (both regions)
$L_H = (1-\alpha)/2$	0.1	housing labour (per region)
$\overline{L} = \overline{L}_M + \overline{L}_H = 1$	1	total labour (both regions)
$\overline{K}_M = K_M + K_M^* = 1$	1	total capital use in manufacturing (both regions)
$0 \le s \le 1$	0.75	commuter share in the centre (*own calculation for Graz area*)
$0 \le s^* \le 1$	0.75	commuter share in the hinterland (*own calculation for Graz area*)

Recall from Section 2 that we assume emissions to be caused by passenger transport. Moreover, we distinguish between four groups of workers that differ by region of residence and whether they commute or not (see Table 3).

Table 3: The four groups of workers, workforce and residence per region, group-specific PM_{10} emission factors per person-kilometer and group-specific emissions per trip

	groups	share in workforce	emission factor	emissions
			[g/p-km]	[g/trip]
non-commuters				
centre	group 1	0.75	0,040	0,04
hinterland	group2	0.75	0,043	0,22
commuters				
to hinterland	group 3	0.25	0,064	0,64
to centre	group 4	0.25	0,063	0,63
workforce				
centre	groups 1 + 4 (= λ)			
hinterland	groups 2 + 3 (= 1- λ)			
residents				
centre	groups 1 + 2			
hinterland	groups 3 + 4			

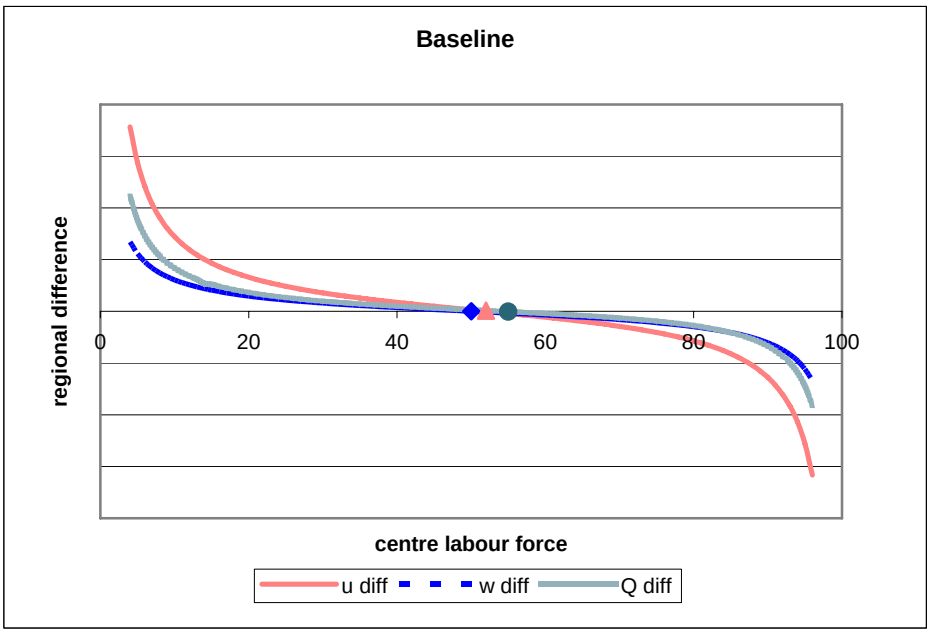
Source: Käfer et al. (forthcoming); Hausberger (2007); Steininger et al. (2007); own calculation

For the calculation of group-specific emission factors per person-km (reflecting the modal split) and of group-specific emissions per trip (considering average distances driven) we refer to Koland et al. (2007). In doing so, both PM_{10} emissions as well as the importance of raising PM_{10} and vehicle-related dust are considered. These values will be used in our model runs as follows: 0.22 for group 1, 0.44 for group 2, and 0.64 for groups 3 and group 4. In the following, the values are assumed to be constant.

Let us now describe the baseline solution. Parameter λ refers to the share of the labour force in the centre, so it corresponds to the sum of group 1 and group 4. On the other hand, the centre population of residents is made up of group 1 and group 3. Correspondingly, (1- λ) equals the share of groups 2 and 3, while the hinterland residential population is composed of group 2 and group 4 consumers (see Table 3).

The red (solid) line in Figure 2 depicts the (off-equilibrium) utility differentials for different values of λ, where $\lambda = 1$ is 100%. The green (transparent) line and the blue (dotted) line decompose the utility differential into differences in real income and environmental quality. Equilibrium values of λ are marked where each of these lines crosses the x-axis.

Figure 2: Difference in utility *u – u, real wage *w – w** and environmental quality *Q – Q** for different values of *λ* with *U*=1, *R*=1 and *P*=1**



For the parameters given in Table 1, in equilibrium, i.e. where $u_M = u_M^*$, we find a centre labour force of $\lambda = 0.52$. Due to the differences in environmental damage parameters across regions ($\mu_c < \mu_h^*$), the obtained baseline scenario is thus a reference case with an asymmetric population distribution. In other words, in the baseline solution 52% of manufacturing workers are working in the centre and 48% in the hinterland.

Note that $u_M = u_M^*$ at $\lambda = 0.52$ implies that the positive real wage differential ($w - w^* > 0$) just compensates the negative environmental quality differential ($Q - Q^* < 0$). Thus, the higher real wages in the centre just suffices to compensate for the lower environmental quality in the centre and there exists no pressure to move from the centre to the hinterland or vice versa. If the utility difference is positive (for values of λ below 0.52), the share of manufacturing workers in the centre will increase and vice versa for values of λ between 0.52 and 1.

Note that the figure is limited to illustrating the labour force distribution. The shares of residents per region have yet been quantified; The corresponding share of the worker groups are 38.8% (of the total population) for group 1, 36.2% for group 2, 11.9% for group 3 and 13.2% for group 4 as given below by Table 4. By adding groups 1 and 4 and groups 2 and 3, respectively, residents in the centre are 50.7% of total population and 49.3% in the hinterland.

4.2. The case of urban sprawl

As outlined in the previous section, urban sprawl represents a situation or a process that is characterised by a dispersed settlement structure, with a rising number of commuters on the one hand and a growing share of hinterland residents on the other. This combination entails that external effects in terms of transport-related pollution occur, leading to a degradation of environmental quality in both the centre and the hinterland region.

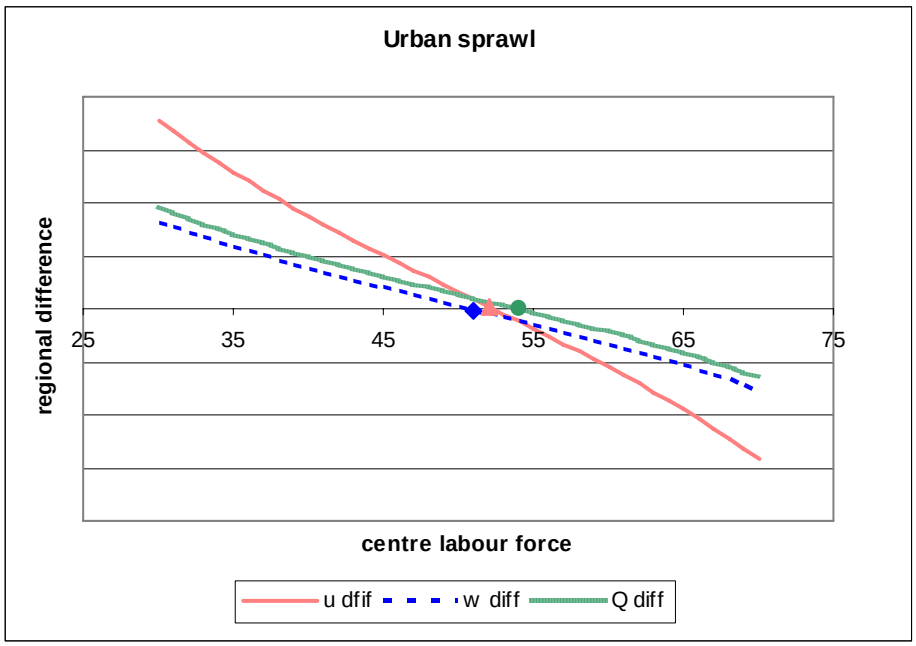
In order to introduce urban sprawl in our model, we let parameter U decrease from 1 to a value of $U = 0.95$, thereby simulating an increase in cross-regional commuters to the centre. The values of the changes in the population distribution between the two regions and the four consumer groups, respectively, which follow this parameter variation in our model, are given by Table 4 (right column). When urban sprawl is present, the number of group 3 commuters rises by 4.2%, that of group 4 commuters by 9.1%. At the same time the hinterland population of residents increases moderately (+0.8%), the hinterland labour force decreases slightly (-0.6%), with reverse effects for the alternative region in each case.

The change in λ, the centre labour force, is depicted by Figure 3. The new equilibrium, where the per capita utility is identical for each region, levels out at $\lambda = 0.523$.

Table 4: The population distribution for the urban sprawl scenario (and changes compared to the baseline)

		Baseline	Urban Sprawl
workforce per region			
centre (=λ)		0,520	0,523
	Δ baseline		*+0,6%*
hinterland (=1-λ)		0,480	0,477
	Δ baseline		*-0,6%*
residents per region			
centre		0,388	0,378
	Δ baseline		*-2,6%*
hinterland		0,362	0,353
	Δ baseline		*-2,5%*
non-commuters			
centre (= group 1)		0,388	0,378
	Δ baseline		*-2,6%*
hinterland (= group 2)		0,362	0,353
	Δ baseline		*-2,5%*
commuters			
to hinterland (= group 3)		0,119	0,124
	Δ baseline		*+4,2%*
to centre (= group 4)		0,132	0,144
	Δ baseline		*+9,1%*

Figure 3: Difference in utility $u - u^*$, real wage $w - w^*$ and environmental quality $Q - Q^*$ for different values of λ with U=0.95, R=1 and P=1 (case of urban sprawl)



5. Policy simulations

Having described the reference case and the case of urban sprawl, we will now discuss the implementation of different policy measures. We select two specific instruments and describe their implementation in the model. We will study two measures: first, a pricing policy (congestion charge), and second, a spatial planning measure (such as the adaptation of provincial land use regulation). These instruments are implemented in the model by changing the parameters *R*, the commuting cost factor, and *P*, the supply level of housing space in the hinterland. In doing so, we investigate the effectiveness of the policies to reach a previously determined environmental target value. I.e. we explore how stringently a pricing and a planning policy have to be implemented to completely internalise the transport related environmental externalities that prevail with urban sprawl, reflecting the optimization problem we are facing.

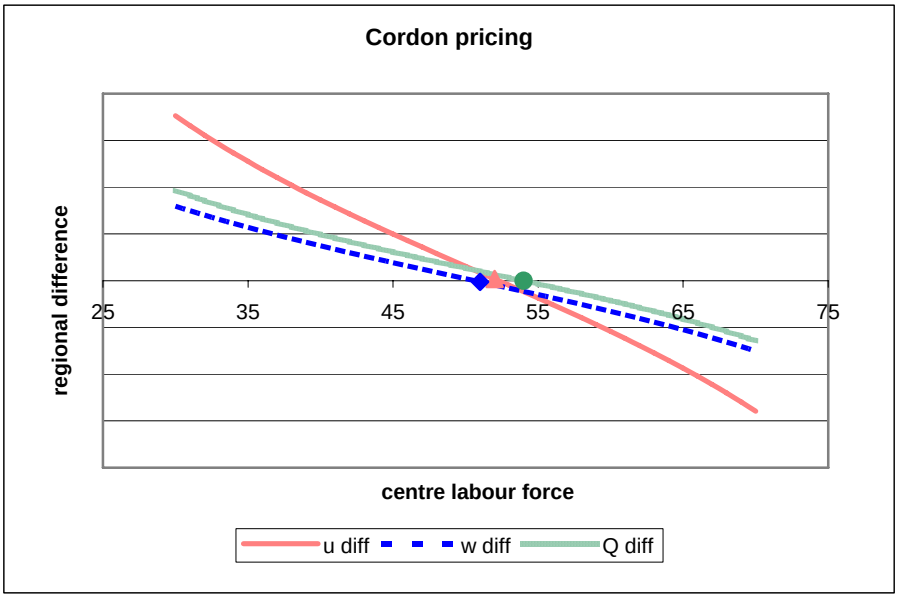
We will first discuss the impact of each measure on the equilibrium population shares (i.e. the labour force and residents per region) and the equilibrium share of the four worker groups and then go on to compare the local environmental impacts of these instruments. The last step is to compare the welfare effect of the two measures given the environmental target level is reached.

5.1. Cordon Pricing

Cordon pricing is a mechanism that charges cars entering a high-activity area such as an urban core. These pricing systems aim at relieving both inner-city congestion and cross-regional congestion due to commuting. At the same time, the implementation of such a policy may result in an improved air quality.

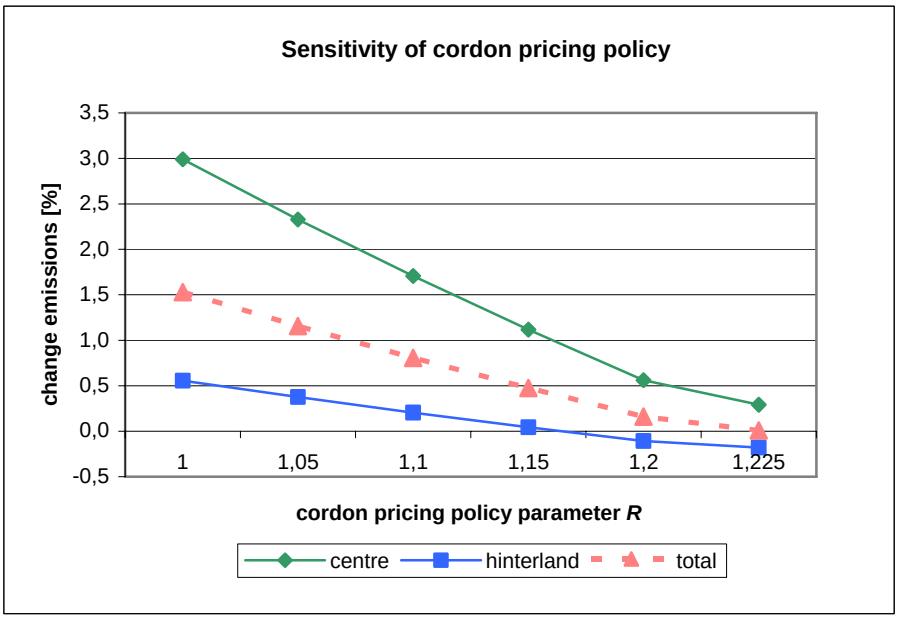
We model cordon pricing by raising the commuting cost factor in the housing market *R*. In our model, this increase represents a change in transport costs in cross-regional commuting in *both* directions, a mobility behaviour that is required due to the disparity between the place of work and the location of residence. The level of commuting costs, where the external environmental effects of transport due to sprawl are internalized, is identified at $R = 1.225$. For this policy value, Figure 4 depicts the regional differentials for levels of utility, real wage and environmental quality. The equilibrium level of λ (which is the sum of group 1 and group 4) very slightly increases relative to the case of urban sprawl.

Figure 4: Difference in utility $u - u^*$, real wage $w - w^*$ and environmental quality $Q - Q^*$ for different initial values of λ with U=0.95, R=1.225 and P=1 (cordon pricing policy)



The sensitivity of R with respect to the change in environmental quality (relative to the baseline) in the centre and the hinterland as well as the effect for both regions in total are illustrated in Figure 5. The figure also shows that at the stringency level of $R = 1.225$, the environmental effects are overcompensated in the hinterland and vice versa in the centre (for exact values see Table 6).

Figure 5: Sensitivity of the cordon pricing policy parameter R with respect to the change in PM_{10} emissions (compared to the baseline).



5.2. Spatial planning

Spatial planning in the hinterland aims at denser housing development, addressing the prevention of excessive urban sprawl. Ideally, with denser housing the environmental impact per capita in the overall region is reduced, enabling public transport services and shorter distances to be traveled. These effects results in lower pollution feedback impact on ever rising urban sprawl.

As a very first step towards such a policy, we restrict the housing supply in the peripheral region. We could think of instruments such as charges for the provision of public infrastructure (aimed at idle building land in central locations), the adoption of land use regulation or the restructuring of funding for residential property. The implemented restriction helps us to find out about partial effects of an overall planning measure.

In order to integrate the policy in our model, we implement a change in the supply level of housing space in the hinterland P. More specifically, we reduce production inputs in hinterland housing. We let parameter P decrease to P=0.66, reflecting a restriction of housing space in the hinterland at a stringency level that totally internalizes the environmental externalities from urban sprawl.

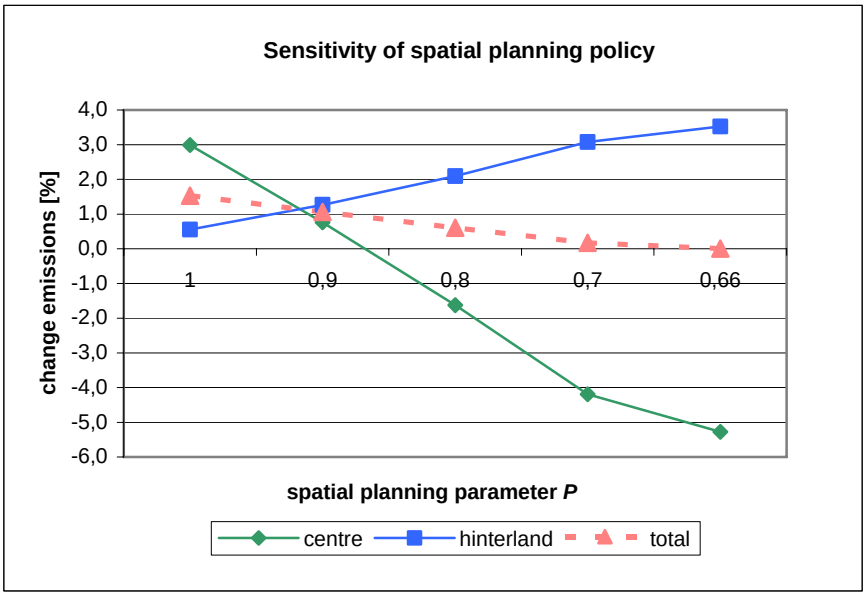
Figure 6: Difference in utility $u - u^*$, real wage $w - w^*$ and environmental quality $Q - Q^*$ for different initial values of λ with U=0.95, R=1 and P=0.66 (spatial planning policy)

While cordon pricing gradually improved the environmental quality in both regions, we find from Figure 7 that a spatial planning measure in the hinterland with a stringency of P=0.66 has varying effects on the centre and the hinterland emissions, with a strong improvement in environmental quality in the centre and degradation in the hinterland (compared to the baseline), summing up to a zero total change in quality (full internalization). For the full internalization level

P=0.66, Figure 6 depicts the regional differentials for levels of utility, real wage and environmental quality for different values of λ. There is a moderate increase (+4.4%) in the equilibrium level for λ to a value of $\lambda = 0.546$.

The sensitivity of *P* with respect to the change in environmental quality in the centre and the hinterland as well as the effect for both regions in total are illustrated in Figure 7.

Figure 7: Sensitivity of the spatial planning policy parameter *P* with respect to the change in PM_{10} emissions (compared to the baseline).



5.3. Effects on location of residence and commuting

The instrument of cordon pricing affects interregional commuter flows in both directions i.e. flows form the centre to the hinterland region and vice versa. Thus, this instrument combats the rise in commuters that has been induced by urban sprawl. As shown in Table 5, group 3 and group 4 commuters decline in numbers relative to the urban sprawl scenarios (-6.5% and -6.9%), which is compensated by a rise in intraregional commuters groups (group 1 and group 2). Moreover, the number of residents in the hinterland falls slightly (-0.4%), indicating that consumers start to move back to the centre to live in the region where they work.

In order to analyse the impacts of a spatial planning instrument in the hinterland, we have to take account of the fact that this measure mainly affects the groups of those residents who live in the peripheral region. Overall, restricting the supply of housing has very strong effects on the population distribution. Outstanding are the dramatic fall in hinterland residents (-15.7%) and its corresponding rise for the centre population (+15.5%). Thus, the restriction of housing by setting the full internalization level *P*=0.66 operates strongly on the consumers' housing decision, driving up hinterland housing prices and reducing the incentive to resettle to the outer region. Effects regarding the labour force are weaker, yet still quite strong

(+4.4% for the centre and -4.8% for the hinterland). The impact on the hinterland residential population corresponds to the considerable fall in the size of those consumer groups, who live in the hinterland, namely group 2 (-14.2%) and group 4 (-19.4%). Analogously, we find an incentive to live in the centre region; the remaining groups (groups 1 and 3) thus undergo a significant rise in size (+13.8% and +21.8%).

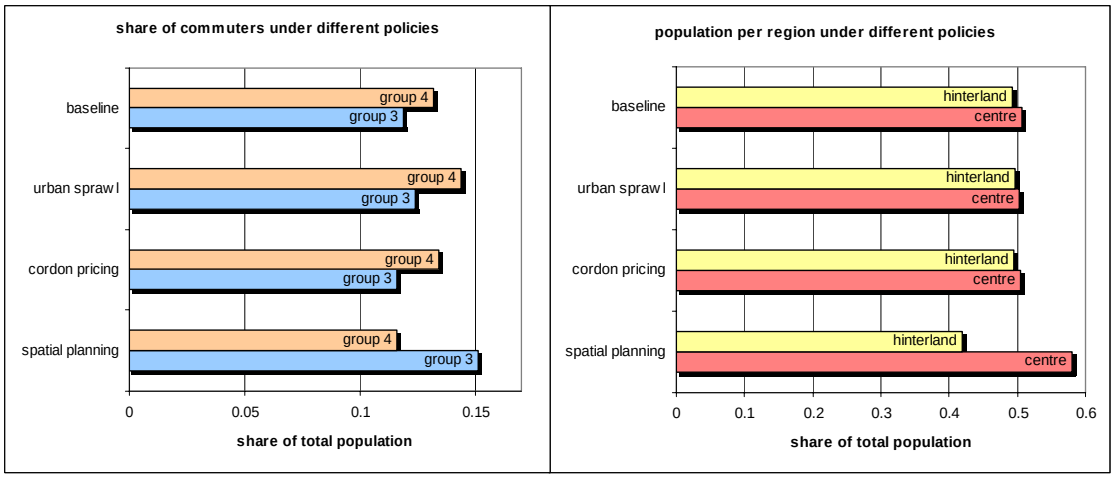
Table 5: The population distribution for the policy scenarios (and changes compared to the urban sprawl scenario)

		Urban Sprawl	Cordon Pricing	Spatial Planning
workforce per region				
centre (=λ)		0,523	0,523	0,546
	Δ urban sprawl		*+0,0%*	*+4,4%*
hinterland (=1-λ)		0,477	0,477	0,454
	Δ urban sprawl		*+0,0%*	*-4,8%*
residents per region				
centre		0,503	0,505	0,581
	Δ urban sprawl		*+0,4%*	*+15,5%*
hinterland		0,497	0,495	0,419
	Δ urban sprawl		*-0,4%*	*-15,7%*
non-commuters				
centre (= group 1)		0,378	0,389	0,430
	Δ urban sprawl		*+2,9%*	*+13,8%*
hinterland (= group 2)		0,353	0,362	0,303
	Δ urban sprawl		*+2,5%*	*-14,2%*
commuters				
to hinterland (= group 3)		0,124	0,116	0,151
	Δ urban sprawl		*-6,5%*	*+21,8%*
to centre (= group 4)		0,144	0,134	0,116
	Δ urban sprawl		*-6,9%*	*-19,4%*

5.4. Environmental impacts

Based on changes settlement structures and commuting flows we evaluate the environmental impacts of the implemented policies. For this reason let us have a look at the share of cross-regional commuters (left graphics in Figure 8) and the population per region (right graphics) in each scenario again.

Figure 8: Commuting flows (group 3 and group 4) and settlement structure (centre and hinterland residents) under different scenarios.



Recall that we assumed pollution to be prompted to a large part by commuting residents. Moreover, from Section 4 we know that transport related emissions are different for each commuter group due to differences in modal split and vehicle miles travelled. The highest impacts from commuting stem from cross-regional trips (groups 3 and 4), where distances are longest and car dependency is high. They are followed by commuting trips within the hinterland, mainly because group 2 is characterized by a low share of public transport. By contrast, trips within the centre region are less car dependent and do not involve substantial distances to be travelled; so the impact is lowest within group 1. Due to our assumption of constant emission factors per trip and group, environmental effects are linear in the number of workers.

It is important to take into account the type of pollutant when aggregating environmental impacts. While for global pollutants such as CO_2 the location of emission is irrelevant, for local pollutants like PM_{10} the location of emission is essential. In this vein, it is equally important to know where pollutants such as particulate matter accumulate (i.e. the ambient level) and where emissions are originally caused. In order to capture that difference, we report environmental effects per region and for both regions in total in Table 6.[9]

Both cordon pricing and spatial planning are imposed such that they lead to an improved aggregated environmental quality over both regions (full internalization level). For each of the instruments we find the following.

The improved environment induced by *cordon pricing* stems from a decrease in the number of cross-regional commuters (groups 3 and 4) whose emission factors are highest. Table 1 reports on the respective environmental damage parameters, i.e., $\mu_3 = \mu_4 = 0.64$ for groups 3 and 4. The reduction in interregional commuters suggests that emissions of pollutants will be mitigated because vehicle miles travelled decrease, and there is a lower car dependency in the overall region. As a

[9] Recall that in order to calculate the pollution levels per region we assumed group 3 to contribute to the hinterland level and group 4 to the centre level.

consequence, cordon pricing improves the level of environmental quality in both regions, with a stronger effect in the centre region; here the ambient level of PM_{10} declines by 2.6% relative to a situation of urban sprawl. For both regions in total, emissions are mitigated by 1.5% compared to urban sprawl, which corresponds to a complete internalization of mobility related externalities, thereby restoring the reference level of environmental quality (baseline). The values are reported in Table 6.

The *spatial planning* measure reduces overall pollution by counteracting out-migration. The general reduction in transport related pollutants is due to less residents in the hinterland (i.e., a decline in group 2 and group 4 workers), via the induced rise in hinterland housing prices. However, the reduction in housing supply has now also induced new transport by a considerable rise in residents who commute from the centre to the hinterland (group 3 increases). For spatial planning, the ambient level of PM_{10} thus decreases considerably in the centre (-8%), as shown in Table 6, and rises moderately in the hinterland (+ 3%). Taking the effects for the centre and the hinterland together, the overall level of pollutants equals the baseline level. The implemented policy has therefore internalised the transport related externalities induced by urban sprawl.

Table 6: PM_{10} emissions for the policy scenarios cordon pricing and spatial planning (and changes compared to the baseline and the urban sprawl scenario)

		Baseline	Urban Sprawl	Cordon Pricing	Spatial Planning
		PM_{10}	PM_{10}	PM_{10}	PM_{10}
		[tons/year]	[tons/year]	[tons/year]	[tons/year]
effect per region					
centre		153,366	157,950	153,813	145,274
	Δ urban sprawl			*-2.6%*	*-8.0%*
	Δ baseline		*+3.0%*	*+0.3%*	*-5.3%*
hinterland		230,009	231,285	229,595	238,115
	Δ urban sprawl			*-0.7%*	*+3.0%*
	Δ baseline		*+0.6%*	*-0.2%*	*+3.5%*
total effect		383,375	389,235	383,408	383,389
	Δ urban sprawl			*-1.5%*	*-1.5%*
	Δ baseline		*+1.5%*	*+0.0%*	*+0.0%*

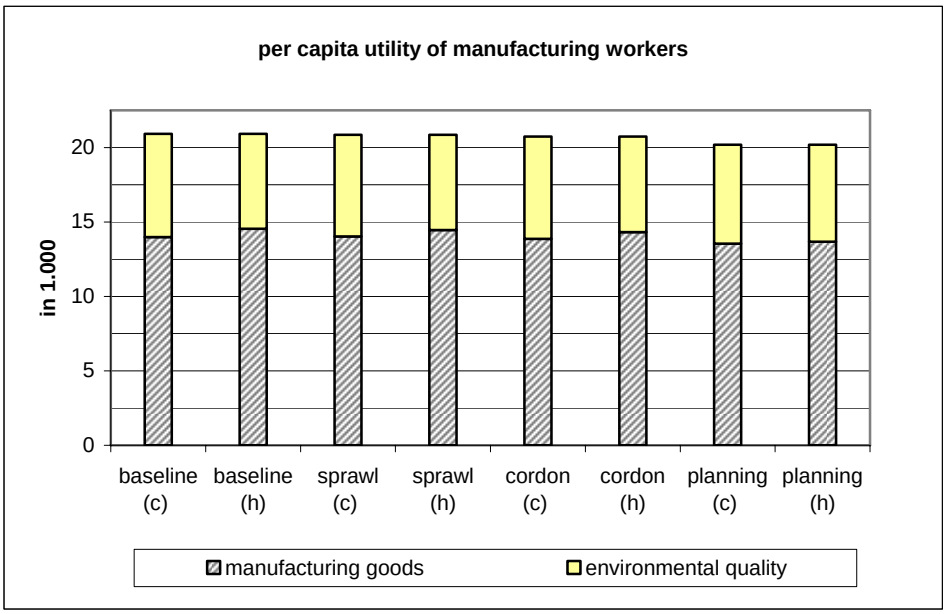
5.5. Effects on utility levels

As a first step towards a welfare analysis, we explore the level and composition of per capita utility levels of the manufacturing workers (i.e. those residents who are mobile between regions in the model). The reason is that the model does not include government revenues and expenditures.

Note that, by definition of an equilibrium, the per capita utility per region is balanced for the centre and the hinterland for each policy scenario. The level of per

capita utility, though, varies across scenarios as well as the combination of manufacturing goods *M* and environmental quality *Q*. Figure 9 shows the respective utility levels.

Figure 9: Per capita utility of manufacturing workers from manufacturing goods *M* and environmental quality *Q* for the centre (c) and the hinterland (h) region and for each scenario



While per capita utility levels are slightly decreasing with urban sprawl (-0.2% compared to the baseline), they further fall moderately with cordon pricing (-0.6%) and considerably with spatial planning (-3.3%) (both compared to the case of urban sprawl). From that we conclude that the simulated restriction of housing supply in the hinterland (via planning) represents a major intervention and has significant effect on utility and welfare levels, respectively. We also conclude, however, that the external effect from transport is not modelled adequately for the moment. This can be seen from the merely changing welfare level induced by sprawl.

Moreover, the contribution of manufacturing goods *M* to utility decreases in both regions in both policy scenarios, yet to a stronger degree in case of a planning measure. On the other hand, the contribution of environmental quality *Q* differs: Cordon pricing operating symmetrically increases the contribution of *Q* in centre and periphery, whereas it falls in the centre and rises in the hinterland for the planning measure, reflecting the one-sided effect of this policy.

6. Summary and conclusions

This paper tried to explain the driving forces for the suburbanisation of urban areas and its link to commuting and environmental concerns. First we extended a standard core-periphery model to integrate housing and environmental concerns; then the theoretical framework was expanded to the empirical domain. With this

model, we are able to analyse the main determinants of urban sprawl and policy instruments to address its environmentally harmful implications.

Since the number of commuters and non-commuters determine the region-specific level of environmental quality and since environmental quality contributes to household utility, environmental quality affects the location decision of households in the long run. If the environment differs across regions, a lower environment has to be compensated for by higher consumption quantities of the manufactured and/or housing commodity. Moreover, since housing production is fixed in quantitative terms yet workers are mobile across regions, the arising changes in housing prices induce a fraction of the population to resettle to the cheaper region. A spatial equilibrium thus implies that the regional difference in real income is compensated by the difference in environmental quality.

In addition to a baseline scenario, we construct an urban sprawl scenario to reflect the present trend in many urban agglomerations. Different environmental damage parameters for different types of commuting imply an asymmetric population distribution in the long term, with a larger fraction of residents located in the region with lower overall environmental impacts. If the strength of consumers' environmental preferences increases, this population share rises, too, reinforcing the dispersed population distribution.

In our policy analysis, we first investigate the effects of a congestion charge in order to reduce the number of cross-regional commuters. Second, we look at the consequences of a spatial planning instrument such that zoning plans in the hinterland are more stringent, i.e. reducing the effective housing supply in the hinterland. We identify the stringency levels necessary to fully internalize the environmental consequences of urban sprawl relative to the baseline level (without sprawl). In evaluating these policy options we find the following.

Firstly, both instruments generally reduce urban sprawl, though they do so through different channels. Cordon pricing curbs sprawl by addressing cross-regional commuters. By contrast, a planning measure is capable of reducing the degree of urban sprawl due to the arising rise in property prices in the addressed region. Secondly, spatial planning policy has in general stronger effects on the settlement structure than does a pricing policy. Thirdly, the shift between the consumer groups – both in magnitude and direction – is different for the two policies. While cordon pricing operates symmetrically and addresses residents who commute between the regions, spatial planning has ambiguous effect for the two regions. In particular, with cordon pricing the direction of change is the same for non-commuters on the one hand and commuters on the other hand. Implementing a spatial planning instrument, however, leads to similar effects for workers who live in the region addressed by the policy measure.

Regarding environmental impacts, both policies lead to desirable effects for the overall region, yet with different effects for ambient levels of PM_{10} per region. The reason is that cordon pricing most strongly curbs the total number of cross-regional commuters, driving long distances with car dependent modal shares, which

improves the environment. On the other hand, instruments restricting housing supply in the hinterland do so by applying to residents who commute to the centre and to those who drive long distances within the hinterland region. Hence, from a regional perspective, the pricing policy is connected to favourable emission reductions in both regions, whereas the hinterland planning measure has ambiguous results from an environmental perspective (with an improvement for the centre, but a degradation for the hinterland).

Aiming at the internalization of the environmental effects of urban sprawl, it becomes clear that policy measures relevant for the development of the transport sector should also address the spatial distribution of economic activities rather than transport flows per se. Emission impacts from passenger transport can thus be mitigated by addressing the distribution of workplaces and residences and, accordingly, by steering the number of commuters between regions.

The attempt to study regional welfare effects was weakened by the absence of government revenues and expenditures in the model. Instead, we carried out an analysis of per capita utility levels, serving as a preliminary welfare approach. The results reflect the basic characteristics of the two policy instruments with respect to regional symmetry, i.e. direction, and magnitude of their effects.

The presented model and its results can be regarded as an important but still preliminary step towards jointly modelling transport and housing decisions in a multi-regional context. While we are able to reproduce stylised effects of urban sprawl and analyse the impacts of different transport and planning instruments, paths for future development emerge along several lines. One is to fully implement an explicit modelling of mode choice, both within and across regions. For instance, a spatial planning measure aimed at denser living leads to changes in the emissions per trip by promoting public transport infrastructure and enabling an improved possibility to switch to more environmentally favourable modes. Another aspect to capture the character of denser housing structures would be to model the creation of mixed use areas, allowing for a minimization of transport distances. These effects taken together would then result in significantly lower pollution feedback impact on ever rising urban sprawl. A third idea would be to improve the modelling of welfare effects by comprehensively depicting transport related externalities and by including budget constraints of public authorities.

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Appendix

A.1 Stability of the symmetric equilibrium for identical regions

For the derivation of $du_M/d\lambda$ as given in equation (25), we make use of the fact that around the symmetric equilibrium all endogenous variables are identical in both regions. Thus, the values $\lambda = ½$, $w_M + p_K c_M = y_M = 1$ and $p_H = 1$ hold in both the centre and the hinterland. This yields $Y = ½$, $G^{1-\sigma} = (1+T^{1-\sigma})/2$, $Z = (1-T^{1-\sigma})/(2G^{1-\sigma})$, $L_M = \alpha/2$ and $K_M = ½$; the variable Z follows as an index of transport costs defined as $Z \equiv (1-T^{1-\sigma})/(1+T^{1-\sigma})$ with $0 \le Z \le 1$.[10] The second important point is that any change in a variable in one region is matched by an equal but opposite sign change in the other region. Thus, we let $dG = -dG^*$, $dL_M = -dL_M^*$, $dy_M = -dy_M^*$, $dY = -dY^*$, and $dp_H = -dp_H^*$. Furthermore we let the environmental impact factors be equal across regions, i.e. $\mu_c = \mu_h^*$ and $\mu_h = \mu_c^*$, which finally gives $du_M/d\lambda = -du_M^*/d\lambda$. Then, the total differential of the per capita utility, using the above indicated values, is

$$\begin{aligned} du_M &= d\omega + \delta\, dQ = \\ &= G^{-\alpha}(R^{1-\beta})^{-(1-\alpha)}\Omega\left(dy_M - \alpha\frac{dG}{G} - dp_H(1-\alpha)(2\beta-1)\right) + \\ &+ \delta\,\frac{2dp_H\, e^{\frac{-\beta R\mu_c-(1-\beta)\mu_h}{\beta(R-1)+1}} R(1-\beta)(\mu_c-\mu_h)}{(\beta(R-1)+1)^2} \end{aligned} \tag{A1}$$

with $\Omega = \alpha^\alpha(1-\alpha)^{1-\alpha}(\beta^\beta(1-\beta)^{1-\beta})^{1-\alpha}$. Totally differentiating equations (19) to (22) yields

$$dy_M = \frac{2ZdY}{\sigma} + Z\frac{(\sigma-1)}{\sigma}\frac{dG}{G} \tag{A2}$$

$$dY = \alpha\, d\lambda + \frac{\alpha\, dy_M + (1-\alpha)\, dp_H}{2} \tag{A3}$$

$$\frac{dG}{G} = \frac{2Z}{1-\sigma}d\lambda + Zdy_M \tag{A4}$$

$$dp_H = 2dY\frac{\beta\,(1+R)-1}{R} \tag{A5}$$

In order to find out whether $\lambda = ½$ is a stable distribution for specific parameter values, we substitute equations (A2)-(A5) into (A1), resulting in the change in per capita utility caused by a relocation of residents:

[10] When there are no transport costs, i.e. $T = 1$ (free trade), the index $Z = 0$. When, on the other hand, transport costs are prohibitively high, i.e. $T \to \infty$ (trade is impossible), $Z = 1$.

$$\frac{du_M}{d\lambda} = \frac{d\omega}{d\lambda} + \delta \frac{dQ}{d\lambda} \tag{A6}$$

$$\left.\frac{du_M}{d\lambda}\right|_{\lambda=0.5} = [\frac{2G^{-\alpha}\left(R^{1-\beta}\right)^{-(1-\alpha)}\Omega}{\sigma-1}[\alpha(1-\alpha)(\sigma-1)\sigma V + \alpha Z(R+\sigma(\beta(1+R)(1-\alpha)+$$

$$+\alpha-2R-1)) + Z^2(-(1-\alpha)(\sigma-1)(V(\alpha\sigma+\frac{0.5}{(\beta-0.5)}) + R(\sigma(1+\alpha^2)-1))] +$$

$$+\delta\frac{4}{(1+(R-1)\beta)^2}e^{\frac{-\beta\mu_c R-\mu_h(1-\beta)}{1+\beta(R-1)}}\alpha\beta\sigma R(\mu_c-\mu_h)(Z^2-1)\ V\frac{1-\beta}{2(\beta-0.5)}]\times$$

$$\frac{1}{\alpha ZR + Z^2(\sigma-1)(-(1-\alpha)\frac{V}{2(\beta-0.5)}+R)+\sigma(\alpha+\beta(1-\alpha)(1+R)-R-1)}$$

where $V \equiv 2(\beta-0.5)(\beta(1+R)-1)$, $Z \equiv (1-T^{1-\sigma})/(1+T^{1-\sigma})$ and Ω as defined in equation (A1).

For the case of $\beta = 0.5$ and $R = 1$ equation (A6) becomes

$$\left.\frac{du_M}{d\lambda}\right|_{\substack{\lambda=0.5\\R=1\\\beta=0.5}} = \frac{2G^{-\alpha}\Omega}{\sigma-1}\frac{[\alpha Z(1-2\sigma+Z^2(\sigma(1+\alpha^2)-1)]}{\alpha Z + Z^2(\sigma-1)-\sigma} \tag{A7}$$

where Z is as defined in (A6) and Ω as in (A1); variable

For the case of $\beta = 1$ equation (A6) turns into

$$\left.\frac{du_M}{d\lambda}\right|_{\substack{\lambda=0.5\\\beta=1}} = 2G^{-\alpha}\Phi\ \frac{[Z(1-\sigma(1+\alpha))-\sigma(1-\sigma)(1-\alpha)(1+Z)]}{(1-\sigma)(\sigma-Z+\sigma Z)} \tag{A8}$$

where $\Phi = \alpha^{\alpha}(1-\alpha)^{1-\alpha}$ and Z as defined as in (A6). Note that $R = 1$ since commuting costs have become irrelevant in the absence of commuting.

A.2 List of variables

Variable	Description
M	manufacturing good (quantity composite)
$m(i)$	consumption of variety i
H	housing
Q	environmental quality
$i = 1, ..., n$, $n^* = 1 - n$	number of varieties/firms
$0 \leq \lambda \leq 1 = n$	share of manufacturing labour in centre
$\lambda^* = 1 - \lambda \quad (= n^* = 1 - n)$	share of manufacturing labour in hinterland
$L_M = \lambda \cdot \alpha$, $L_M^* = (1-\lambda) \cdot \alpha$	manufacturing labour per region
$L = L_M + L_H$	total labour (per region)
$K_M = L_M \cdot c_M$, $K_M^* = L_M^* \cdot c_M$	capital (per region)
w_M	manufacturing wage
$w_H = p_H$, $w_H \neq w_H^*$	housing wage (equals price of one unit of housing)
G	price index consumption good (for one unit of M)
$p_m(i)$	consumer price of variety i
$p_M = p_m(i) \quad \forall i$	producer (f.o.b.) price of variety i
$F \equiv \alpha / \sigma$	fixed labour input in manufacturing
$a_M \equiv \rho$	variable labour input in manufacturing
$q_M = F \cdot \sigma$	manufacturing output of a single firm
$l_M = q_M = F \cdot \sigma = \alpha$	labour demand of a single firm (manufacturing)
$k_M = c_M \cdot l_M$	capital demand of a single firm (manufacturing)
$c_M = 1/(F \cdot \sigma) = 1/\alpha$	capital-to-labour ratio
Y	total (regional) income
y_M	per capita income manufacturing workers
ω	real income in manufacturing
u_M	per capita utility manufacturing workers