
Birgit Friedl a, b, Olivia Koland b, † and Karl Steininger a, b

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a Department of Economics, University of Graz, Universitaetsstraße 15, A-8010 Graz, Austria
b Wegener Centre for Climate and Global Change, University of Graz, Leechgasse 25, A-8010 Graz, Austria
† Corresponding author: Olivia Koland, phone: +43 316 380 8451; fax: +43 316 380 9830; email: olivia.koland@uni-graz.at

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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, with residents mobile between an urban core and its surroundings. To analyse the integrated choice of residence and of commuting, we extend the model for interregional housing market interactions and effects on local environmental quality. In the empirical part of the paper, we solve the model for a stylized urban centre and its surroundings, where urban sprawl leads to detrimental environmental effects. To internalize these environmental effects, we compare the effects of a congestion fee and a spatial planning instrument. While both instruments reduce urban sprawl, they do so through different channels: a change primarily in the share of commuters versus an additional significant change in overall residential pattern. Regarding environmental impacts, both policies lead to desirable effects for the overall region, yet with different effects for levels of pollution per region.

JEL: D58, Q53, R14, R23, R41

KEYWORDS: urban sprawl, commuting, environmental quality, new economic geography, CGE modelling.
1. Introduction

Residential development in many urban areas worldwide is characterized by urban sprawl, triggering significantly increased commuting activity levels and raising concerns over congestion and transport emissions. The aim of this paper is to gain insight into the driving forces in the simultaneous choice of job and residence locations and the population dynamics of an urban region in the long run. We investigate the way in which the moving behaviour of households interacts with the characteristics of residential locations (in particular local environmental quality and housing prices) and with commuting activities. We draw on the now advanced New Economic Geography literature, in which the mutual linkage of transport flows with economic activity levels in the production and household sectors is a dominant feature. For our focus at hand, 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 supply of local environmental amenities and space. The trade-off between these driving factors determines the equilibrium structure of the urban residential distribution. To integrate these features we modify a standard core-periphery type model and also implement this model in the empirical domain to compare policy measures to overcome transport induced negative environmental externalities of urban sprawl.

Let us start with an overview of the core features serving our purpose of the 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 dispersion 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 (2008). Suedekum’s (2006) model implies that the true costs of living may be higher in the centre region, contradicting standard CP model predictions. He builds on the integration of housing scarcity as a main determinant of regional price differentials. By contrast, Pflueger and Suedekum (2008) investigate the welfare effects of agglomeration and the efficiency of policy intervention. What these two papers share 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, 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 transport costs for interregional commodity supply 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.

Okamoto (2007) extends this line of thought to a setting of a larger number of differentiated districts within a single city. She introduces heterogeneity in skills and preferences of workers, both determining their preferred residence location, and she endogenously explains the existence of cross-commuting over district borders as long as they are close enough to the city centre through which commuting is taken to pass through. Okamoto thus develops a model of continuous space with cross-commuting within a single city.

Regarding environmental concerns, Quaas and Lange (2007) extend the canonical CP model to include local environmental pollution, which is caused by production and thus linked to a concentration of skilled labour. Urban environmental problems act as a dispersing force, because they make agglomerations less favourable. In comparison to Krugman’s results, their model can explain a third type of equilibrium, i.e. a stable asymmetric and incomplete agglomeration of skilled workers in one of the two regions. Note that pollution in Quaas and Lange is caused by production as in Verhoef and Nijkamp (2002), Arnott et al. (2004),
Marrewijk (2005) and Yoshino (2004). By contrast, an urban general equilibrium model with pollution from commuting was developed by Verhoef and 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.

In order to understand regional differences in population density, the NEG has thus dealt mainly with firms’ location of production, and - when environmental concerns were included - with pollution from production. In a complementary effort, the present paper focuses on consumers’ decisions in order to understand the development of population density. For that end it allows for a differentiation between place of work and residence, and also focuses on environmental pollution from consumption.

We model an economy consisting of two regions, an urban core and its surroundings. The framework is based on various modifications of Krugman’s (1991) 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, we extend Suedekum’s (2006) framework to include environmental quality. We do so in the basic spirit of Quaas and Lange (2007) and Eppink and Withagen (2006). Yet, contrary to them and other typical environmentally-oriented models that cover pollution from production (e.g. Marrewijk, 2005; Yoshino, 2004), we assume pollution to be caused by commuting residents, i.e. the intensity of mobility activities (expressed by the dimension of urban sprawl) is affecting the level of environmental quality. Alternatively seen – i.e. approaching our endeavour from the opposite direction – we introduce a housing market into a consumer-oriented modification of the model by Quaas and Lange (2007). We do this in the spirit of
Suedekum (2006), yet with the crucial additional extension that we let housing 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 mobility behaviour.

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 (interregional commuting). In the empirical part of the paper, we set up a stylized centre/surroundings 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, while the existence and stability of equilibria are 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. We then outline the CGE effects of these policies on urban residential distribution, on commuting flows and on environmental quality per region. Section 6 summarizes the results and concludes.

2. The model

2.1. Regions and their factors of production

The economy consists of two regions, an urban core and its surroundings, which we distinguish by an asterisk (*). It 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 only so that \( p_{HH} = w_{HH} \) and \( p^* = w^*_HH \). There are three (sector-specific) factors of production: While labour used in the housing production \( L_{HH} \) is immobile and equally distributed between core and the surrounding area, manufacturing workers \( L_M \) are interregionally mobile, thereby determining a specific settlement structure. Moreover, capital \( K_M \) is freely mobile across regions. For the reference scenario, we choose units for the supply of manufacturing workers \( \alpha = L_M + L_M^* = \alpha \) and for housing producers \( L_{HH} = L_{HH}^* = (1 - \alpha)/2 \), which yields \( \bar{L}_{HH} = 1 - \alpha \). Consequently, the supply of housing in each region is fixed at \( \bar{H} = \bar{H}^* = (1 - \alpha)/2 \). In addition, \( L = L_M + L_H \) and \( \bar{L} = \bar{L}_M + \bar{L}_H = 1 \). Total capital supply is \( \bar{K}_M = K_M + K_M^* \).

2.2. 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 interregional commuters destined for each region (henceforth “commuters”) as well as of residents working within the same region (“non-commuters”). The share of commuters in the manufacturing workforce per region is given by \( r \) and \( r^* \). The according damage function \( D(r) \leq 0 \) will be described below. For the moment, let \( D(r) \) affect the level of environmental quality as follows, implying a decrease in environmental quality with rising damage:

\[
Q = e^{D(r)} \quad \text{and} \quad Q^* = e^{D(r^*)}.
\]

All workers are final consumers and share the same preferences on \( Q \), the composite manufacturing good \( M \) and housing \( H \). Environmental quality \( Q \) enters the utility function directly in an additively separable form:
\[ U(M,H,Q) = M^\alpha \left[ (H_c)^\beta (H_s)^{1-\beta} \right]^{\frac{1}{1-\alpha}} + \delta Q \quad \text{with } 0 \leq \alpha \leq 1 \text{ and } \beta \neq 0.5. \quad (2) \]

For workers of the centre region, \( H_c \) is housing in their own region, the centre, and \( H_s \) is housing in the external region, the surroundings, which is thus connected with commuting. Parameter \( \beta \) indicates the preference for commuting, with \( \beta = 1 \) indicating full aversion to commuting. Thus, for the workers in the housing production, since they are immobile between the regions \( \beta = 1 \), for the manufacturing workers \( 0 < \beta < 1 \). 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 \( i \in ]0; \hat{n} [ \) and let \( \sigma = 1/(1-\rho) \) indicate the constant elasticity of substitution in preferences between any pair of varieties,

\[ M = [u(m(i))^\rho + n^*(m(j))^\rho]^\frac{1}{\rho} \quad \text{with } 0 < \rho < 1, \quad (3) \]

where the consumption of each local variety is denoted by \( m(i) \) and of each “imported” variety by \( m(j)^* \). Centre varieties \( n \) belong to the interval \( ]0; \hat{n} [ \) and external varieties \( n^* \) belong to the interval \( ]n; \hat{n} [ \). 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:

\[ Y = p_H H_c + R p_H^* H_s + G \cdot M \quad \text{with } R \geq 1, \quad (4) \]

where \( G \cdot M = n p_m m(i) + n^* p_m^* m(j)^* \). Equation (4) captures the price for housing \( p_H \) in the home region, \( H_c \), and the housing price for demand in the external region, \( H_s \), including commuting costs, \( p_H^* R \), where \( R \) denotes a policy variable setting the commuting cost.
factor.\(^1\) Index \(G\) denotes the price index of the manufacturing composite \(M\) as given in equation (3)\(^2\) and is specified as follows:

\[
G = \left[ n\left( p_M \right)^{1-\sigma} + n^*(p_M^* T)^{1-\sigma} \right]^{1/(1-\sigma)} \quad \text{with } T \geq 1. 
\]

Parameter \(T\) models passenger transport costs in interregional consumption in the iceberg format (von Thünen, 1826; Samuelson, 1952). In the present model, transport costs are incurred whenever residents decide not to buy in the local market but to purchase in the other region.

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

\[
m(i) = \alpha Y \frac{p_m - \sigma}{G^{1-\sigma}} \quad \text{and} \quad m(j)^* = \alpha Y \frac{(p_M^* T)^{-\sigma}}{G^{1-\sigma}},
\]

such that the demand for products manufactured in the centre, made up of its own demand and the demand of the surroundings, including goods to be shipped, adds up to

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

Equations (2) to (7) work analogously for the surroundings. The housing demand of the centre labour force, \(H\), as well as that of the surroundings labour force, \(H^*\), is composed of demand from non-commuters and from residents commuting from outside. Non-commuting residents comprise both manufacturing workers and housing workers in each region. In the following,

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\(^1\) For zero commuting costs \((R = 1)\), the residential choice of manufacturing workers is restricted as follows: \(\beta \neq 0.5\) and \(\beta \neq 1\).

\(^2\) The price index is defined such that \(G\) times \(M\) is equal to expenditure:

\[
\int_0^\delta p_m(i) m(i) \, di = G \cdot M, \quad \text{where} \quad G = \left[ \int_0^\delta p_m(i)^{1-\sigma} \, di \right]^{1/(1-\sigma)} \quad \text{and} \quad M = \left[ \int_0^\delta m(i)^\rho \, di \right]^{1/\rho}.
\]

\(^3\) By assuming the same price for all varieties, for the case of costless transportation, \(G\) (as defined in footnote 2), becomes \(G = p_M^* n^{(1-\sigma)}\)
let letters in the subscript refer to the place of residence, i.e. $c$ for centre and $s$ for surroundings, and let an asterisk distinguish between the regions in terms of the place of work, i.e. an asterisk denotes the surroundings. Thus, the housing demand of non-commuters involves $H_{c,M}$ (manufacturing workers with residence and job location in the centre), $H_{c,H}$ (housing workers in the centre), $H_{s,M}^*$ (manufacturing workers with residence and job location in the surroundings) and $H_{s,H}^*$ (housing workers in the surroundings). By contrast, commuters face higher housing prices due to commuting costs $R$ and demand $H_{s,M}$ (manufacturing workers commuting to the centre) and $H_{c,M}^*$ (manufacturing workers commuting to the surroundings):

$$H_{c,M} = (1-\alpha)\beta \frac{Y}{p_H}$$ and $$H_{c,H} = (1-\alpha)\frac{Y}{p_H}$$ for non-commuters in the centre,

$$H_{s,M}^* = (1-\alpha)\beta \frac{Y^*}{p_H^*}$$ and $$H_{s,H}^* = (1-\alpha)\frac{Y^*}{p_H^*}$$ for non-commuters in the surroundings,

$$H_{s,M} = (1-\alpha)(1-\beta)\frac{Y}{p_H^* R}$$ and $$H_{c,M}^* = (1-\alpha)(1-\beta)\frac{Y^*}{p_H^* R}$$ for commuters, \hspace{1cm} (8)

with $\beta$ defined as in equation (2). Hence, housing demand for each workforce per region, i.e. $H$ for the centre, and $H^*$ for the surroundings, can be written as:

$$H = H_{c,M} + H_{c,H} + H_{s,M}$$ and $$H^* = H_{c,M}^* + H_{s,M}^* + H_{s,H}^*$$ \hspace{1cm} (9)

2.3. Housing market

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 may 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 is fixed at $H^c = (1 - \alpha)/2$ in the centre and at $H^r = P(1 - \alpha)/2$ in the surroundings. The exogenous policy parameter $P$ is initially equal to 1 and will be used to restrict the supply of housing in the surroundings. The housing market is cleared by the Armington assumption of product heterogeneity, which determines the degree to which the trade balance in housing varies.\(^4\) The housing demand of commuters $H_{s,M}$ and $H^*_c$ or, expressed differently, the “exported” quantities of the housing good, are derived from

$$H^*_c = t_{c,0} \bar{H}^c \left( \frac{p_H}{p_H R} \right)^\varepsilon$$ and $$H_{s,M} = t_{s,0} S \bar{R}^s \left( \frac{p_H}{p_H R} \right)^\varepsilon,$$

where $t_{c,0}$ and $t_{s,0}$ denote the reference level of housing exports (at reference housing prices, at the corresponding income, and at $R=1$). Note that for the symmetric case and $R=1$, $t_{c,0} = t_{s,0} = 1 - \beta$. A change in relative housing prices shifts the trade balance in housing, governed by the Armington elasticity $\varepsilon$ 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 exogenous urban sprawl parameter $S$ is initially equal to 1 and will be used to increase the share of housing exports from the surroundings.

Region-specific housing – in contrast to the labour force concept of demand functions in (9) – can be calculated from equation (8) and is composed of home demand and demand from residents who commute to the other region. In equilibrium, the housing supply must equal demand in each region, with $t_c$ and $t_s$ representing the share of housing exports:

$$H^c = (1-t_c)\bar{H}^c + t_c \bar{H}^c = H_{c,M} + H^*_c + H^*_c, \quad \text{for the centre, and}$$

$$H^r = (1-t_s)\bar{H}^r + t_s \bar{H}^r = H_{s,M} + H^*_s + H^*_s, \quad \text{for the surroundings.} \quad (11)$$

\(^4\) Under the Armington assumption, domestic housing goods are treated as qualitatively different from housing goods imported from the other region.
2.4. 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 pollution caused are only due to travelling to work. Both commuters and non-commuters 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 surroundings (group 2), commuters originating in the centre (commuters to the outlying region) (group 3), and commuters originating in the external region (commuters to the centre) (group 4). To model these groups, we first need their share in the manufacturing labour force per region, with \( r \) representing the commuter share in the centre, and \( (1-r) \) representing the centre’s non-commuters. The shares are defined analogously for the surroundings,

\[
\begin{align*}
 r = \frac{H_{c,M}}{H_M}, & \quad (1-r) = \frac{H_{c,M}}{H_M}, \quad r^* = \frac{H_{c,M}^*}{H_M^*} & \quad \text{and} & \quad (1-r^*) = \frac{H_{s,M}^*}{H_M^*} .
\end{align*}
\]

(12)

with \( H_M = H_{c,M} + H_{s,M} \) and \( H_M^* = H_{c,M}^* + H_{s,M}^* \). To calculate the levels of environmental quality per region, we assume that commuters to the centre contribute to the centre level of environmental quality \( Q \) and commuters to the surroundings contribute to the outlying level \( Q^* \). Moreover, each type of worker causes pollution by a group-specific environmental impact factor, which we denote by \( \mu \). Thus, the damage functions \( D(r) \) and \( D(r^*) \) from equation (1) can be specified as

\[
D(r) = -(\mu_c (1-r) + \mu_s r) \quad \text{and} \quad D(r^*) = -(\mu_c^* (1-r^*) + \mu_s^* r^* ) .
\]

(13)

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5 The environmental impact factor is governed by modal split and trip distance of each group, which we take from empirical observations and constant. Takahashi (2006) develops a stylized economic geography model of endogenous choice among one of two transport technologies, thereby explicitly depicting the interaction of mode choice with spatial density in residence. His analysis focuses on transport in interregional consumption. Analysing transport in commuting, however, opens a different set of interactions, most notably via interregional differentials in wages and housing prices, as is the focus of the present paper.
2.5. Manufacturing

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 $a_M$:

$$l_M = F + a_M q_M.$$  \hspace{1cm} (14)

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 $c_M = k_M/l_M$, 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, $\sigma = 1/(1-\rho)$, give the profit-maximising price $p_M$ for each variety as a fixed mark-up over marginal cost. Including the normalisation $a_M = \rho$, this yields

$$p_M = \frac{a_M (w_M + p_k c_M)}{\rho} = w_M + p_k c_M = y_M,$$  \hspace{1cm} (15)

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 $p_M$ in each region. The resulting outcome, i.e. an
equilibrium for a given distribution of manufacturing workers over the two regions (denoted by $\lambda$ as specified below) 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.

As in Fujita et al. (1999) we use the standard normalisations $a_M \equiv \rho = (\sigma - 1)/\sigma$ and $F \equiv \alpha/\sigma$. Recalling that total labour supply $L_M = \alpha$, in an 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 $M = L_M/L_M, 0 < \lambda < 1$, 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 (15) gives us the first pair of equilibrium conditions, i.e. the income of a manufacturing worker at which firms break even (16). Instantaneous equilibrium is characterised by the following eight equations:

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

(16)

with $n = \lambda = L_M/\alpha$, $p_M = y_M$ and $w_h = p^*_h$ total income $Y$ per region is denoted by

$$Y = \alpha \lambda y_M + p^*_h \frac{(1-\alpha)}{2}, \quad Y^* = \alpha (1-\lambda) y_M^* + p^*_h \frac{(1-\alpha)}{2},$$

(17)

and the region specific price indices (as given in equation (5)) can be written as
\[ G = \left[ \lambda (y_M)^{1-\sigma} + (1-\lambda)(y_M^* T)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}, \quad G^* = \left[ \lambda (y_M T)^{1-\sigma} + (1-\lambda)(y_M^*)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}. \] (18)

The housing market clears if regional supplies \( \overline{H^c} \) and \( \overline{H^s} \) equal regional demands as given in (11). Hence, housing prices are

\[ p_H = 2[\beta Y + (1-\beta) \frac{Y^*}{R}] \quad \text{and} \quad p_H^* = 2[\beta Y^* + (1-\beta) \frac{Y}{R}]. \] (19)

### 3.2. Long-run equilibrium

To analyse what happens to the settlement structure in the long run, we study how adjustment processes result in a specific population split expressed by the value of \( \lambda \), the share of the centre’s manufacturing labour force in the total manufacturing labour across regions. The driving force in the migration process is the residents’ utility differential between the core and the outlying region.

The representative household splits income \( Y \) between \( M, H_c \) and \( H_s \). Each variety \( m(i) \) and \( m(i)^* \) is chosen in such a way 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

\[ u_M = \omega \Omega + \delta Q = y_M G^{-\alpha} \left( (p_H)^{\beta} (p_H R)^{1-\beta} \right)^{(1-\alpha)} \Omega + \delta e^{D(r)}, \] (20)

where \( y_M \) is per capita income in manufacturing and \( \omega \) its real value, i.e. \( \omega = y_M \left/ \left( G^\alpha \left[ (p_H)^{\beta} (p_H R)^{1-\beta} \right]^{(1-\alpha)} \right) \right. \). \( \Omega = \alpha^\alpha (1-\alpha)^{1-\alpha} (\beta^\beta (1-\beta)^{1-\beta})^{1-\alpha} \) is a constant, and the damage function \( D(r) \) is specified according to (13). The per capita utility 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 (20) evaluated at equilibrium prices.
A long-run equilibrium, i.e. a short-run equilibrium in which the allocation of mobile workers \( \lambda \) is also in equilibrium, occurs when no resident can achieve a higher utility level by changing location. This is the case if per capita utility levels between core and surroundings are equalised, i.e. \( u_M = u_M^* \). We call the according distribution \( \lambda \in [0, 1] \) a \textit{spatial equilibrium}, which arises therefore at

\[
0 < \lambda < 1 \quad \text{when} \quad \Delta u_M = u_M(\lambda) - u_M^*(\lambda) = 0 \quad \text{or at}
\]

\[
\lambda = 1 \quad \text{when} \quad \Delta u_M(1) \geq 0 \quad \text{or at}
\]

\[
\lambda = 0 \quad \text{when} \quad \Delta u_M(0) \leq 0 .
\]

Recall from section 2, that we distinguish four groups of workers: commuters and non-commuters who either live in the centre or in the surroundings. According to (12) and acknowledging that commuter shares depend on the equilibrium centre labour force \( \lambda \), these groups, \( g_1, g_2, g_3 \) and \( g_4 \), can be written as

\[
g_1 = (1-r)\lambda , \quad g_2 = (1-r^*)\lambda , \quad g_3 = r^*(1-\lambda) \quad \text{and} \quad g_4 = r(1-\lambda) . \tag{22}
\]

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).\(^6\) 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)

\[
\dot{\lambda} = \Delta u_M(\lambda) \lambda (1-\lambda) \iff \dot{\lambda} = [\omega - \omega^*] + \delta (Q - Q^*) \lambda (1-\lambda) . \tag{23}
\]

Since in the long run no resident has an incentive to relocate, a spatial equilibrium implies \( \dot{\lambda} = 0 \). The utility differential \( \Delta u_M \) comprises differences in real income \( \omega \) and environmental quality \( Q \). If the differential is positive, there is an incentive for some workers to move from the surrounding area to the centre, and vice versa for a negative differential. In this way, the

\[^6\] In particular, \( \dot{\lambda} = d\lambda/dt = (u_M - \bar{u}_M)\lambda \) with \( \bar{u}_M = \lambda u_M + (1-\lambda)u_M^* \), and \( t \) is time.
urban residential dynamics is an outcome of all the households’ simultaneous individual choices.

3.3. Existence and stability conditions

We shall investigate the existence of equilibria by means of equations (21) and (23). The most obvious spatial equilibrium arises with equality in real income $\omega$ and environmental quality $Q$ across regions. For this equality, it can easily be seen that the utility differential is zero. Alternatively, the difference in real income levels may be compensated for by the reverse difference in environmental quality. In particular, the spatial equilibrium in this case is characterised by either $\omega > \omega^*$ and $Q < Q^*$, or $\omega < \omega^*$ and $Q > Q^*$. Thus, for a lower $\omega$ (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.

A spatial equilibrium is asymptotically stable if, for any marginal deviation of the population distribution from the equilibrium, the model dynamics bring the distribution of mobile labour back to the equilibrium level.\footnote{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 (20) remains valid for the new settlement structure of residents. Then, wages are adjusted such that firms earn zero profits.} 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 $\Delta u_M$ 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 $\lambda = \lambda^*$. With identical regions this must be an equilibrium since $\omega = \omega^*$ and $Q = Q^*$ and thus $u_M = u_M^*$. By totally differentiating (20) around the symmetric steady state with respect to $\lambda$...
we derive \( du_M / d\lambda \), the equilibrium respond, which is the change in per capita utility caused by a movement of residents:

\[
\frac{du_M}{d\lambda} = \frac{d\omega}{d\lambda} + \delta \frac{dQ}{d\lambda}.
\]  

(24)

For the full notation of (24) and its derivation we refer to Appendix A.1. If \( du_M / d\lambda \) is negative for the exogenous parameter values of \( \sigma, \alpha, \delta, \mu, T \) and \( R \), the symmetric case \( \lambda = \frac{1}{2} \) is a stable equilibrium and vice versa for a positive value. Moreover, the symmetric solution is characterized by identical environmental damage parameters across regions.

4. The CGE model

To analyse the core forces in urban sprawl, we implement the theoretical model as characterised by equations (16), (17), (18) and (19) in a CGE format. We thus numerically solve this system and therefore apply spatial computable general equilibrium analysis.

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 surroundings. As a consequence, the equilibrium value of \( \lambda \) 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 for any exogenous reason commuting to the centre is enhanced and thus the residential population in the surrounding area 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.

---

8 Then, for the parameter values \( \sigma = 5 \) and \( \alpha = 0.8 \) (see Table 1), we find that the symmetric case is a stable equilibrium \( (du_M / d\lambda < 0) \).
4.1. The reference specification and the baseline scenario

As a first step, we briefly describe the (long-run) equilibrium in the case without policy interventions. This case will serve as a reference case for the purpose of comparing the policy simulations. Let us first specify exogenous parameters and initial variables as introduced in the theoretical model in order to calibrate the reference equilibrium (see Koland et al., 2008, for parameterization); the values are given in Table 1. For the description and normalizations of the remaining variables we refer to Appendix A.2.

[Table 1 about here]

Let us now describe the baseline solution. Recall from Section 2 that we distinguish between four groups of workers which differ by region of residence and whether they commute or not. Parameter $\lambda$, $0 \leq \lambda \leq 1$, represents the joint share of group 1 and group 4, and therefore refers to the share of the labour force in the centre. It follows that $(1-\lambda)$ corresponds to the sum of group 2 and group 3 (see Table 2). In Figure 1 the red (solid) line depicts the (off-equilibrium) utility differentials for different values of $\lambda$. The green (transparent) line and the blue (dotted) line deconstruct the utility differential into differences in real income and environmental quality. Equilibrium values of $\lambda$ are marked where each of these lines crosses the x-axis.

[Figure 1 about here]

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

Note that the figure is limited to illustrating the labour force distribution. The shares of residents per region as given by equation (11) have yet to be quantified; the corresponding shares of the worker groups are 38.8% (of the total population of manufacturing workers) for group 1, 36.2% for group 2, 11.9% for group 3 and 13.2% for group 4, as given below in Table 2. By adding groups 1 and 3 and groups 2 and 4, respectively, residents in the centre are 50.7% of total manufacturing population and 49.3% in the surroundings.

### 4.2. The case of urban sprawl

As outlined in the previous section, urban sprawl represents a dispersed settlement structure, with a rising number of commuters on the one hand and a growing share of outlying 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 surrounding region.

In order to introduce urban sprawl in our model, we increase the housing export share of the surroundings from initially $t_{c,0} = 0.25$ to 0.288 by setting parameter $S$ to $S = 1.15$. By this means, we simulate an exogenous rise in commuters to the centre. The values of the changes in the population distribution between the two regions and the four consumer groups, which are caused by this change, are given in Table 2 (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 outlying population of residents increases moderately (+0.8%), the outlying labour force decreases slightly (-0.6%), with reverse effects for the centre region in each case. The new equilibrium level of the centre labour force, where the per capita utility is identical for each region, is found at \( \lambda = 0.523 \).

[Table 2 about here]

Based on the shifts within the four groups, we analyse the environmental effects of urban sprawl. Recall that pollution is assumed to be solely caused by passenger transport, leading to a degradation of environmental quality. Mobility related emissions are different for each group of residents due to differences in modal split and vehicle miles travelled. For the calculation of group-specific emission factors we refer to Koland et al. (2008). The highest commuting impacts stem from interregional trips (groups 3 and 4), where distances are longest and car dependency is high. They are followed by trips within the outlying region, 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 environmental impact is lowest from group 1, i.e. \( \mu_c < \mu'_c < \mu''_c = \mu_b \) (see Table 1). Due to our assumption of constant emission factors per trip and group, environmental effects are linear in the number of workers.

It is furthermore 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 accumulate 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 doing so, group 3 contributes to the surrounding pollution level and group 4 to the centre level.
Thus, according to (1) and (13), the increase in commuters caused by urban sprawl leads to a rise in local pollutants for the centre and the surroundings, because their emission factors are highest. Since group 4 rises more than group 3, the deterioration of environmental quality is stronger in the centre (+3% in local pollutants) than in the surroundings (+0.6%). Taken these two effects together, urban sprawl raises the overall pollution across both regions by 1.5% (see Table 4). We thus find an environmental externality to be present with urban sprawl. The internalisation of these external effects by implementing different policy instruments is the focus of the next section.

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: a pricing policy (cordon pricing) and 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 surroundings. In doing so, we investigate the effectiveness of the policies to reach the baseline environmental quality over both regions (comprising $Q$ and $Q^*$). In other words, we explore how stringently a policy has to be implemented to completely internalise the transport related environmental externalities that prevail with urban sprawl. We will then 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.
5.1. Cordon Pricing

Cordon pricing is a mechanism that charges a fee on cars entering a high-activity area such as an urban core. This pricing system aims at relieving both inner-city congestion and interregional congestion due to commuting. At the same time, the implementation of such a policy may result in improved air quality.

We model cordon pricing by raising the commuting cost factor in the housing market $R$ (see equation (4)). In our model, this increase represents a change in transport costs in interregional 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, the equilibrium level of $\lambda$ very slightly increases relative to the case of urban sprawl. With respect to $R$, the sensitivity of the change in environmental quality (relative to the baseline) in the centre and the surroundings as well as the effect for both regions in total are illustrated in Figure 2. The figure also shows that for different stringency levels reductions in local pollutants are stronger in the centre region.

[Figure 2 about here]

5.2. Spatial planning

Spatial planning in the surroundings 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, as it enables public transport services and shorter distances to be travelled. As one possible 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 the development of unused building land in
central locations), the adoption of land use regulations or the restructuring of funding for residential property to foster higher densities.

In order to integrate the policy in our model, we implement a change in the supply level of housing space in the surroundings $P$ (see section 2.3). More specifically, we reduce production inputs in housing outside of the centre. The internalizing level of parameter $P$ is $P=0.66$, reflecting a restriction of housing space in the surroundings compared to the urban sprawl scenario.

While cordon pricing gradually improved the environmental quality in both regions, we find from Figure 3 that a spatial planning measure in the outlying region with a stringency of $P=0.66$ has varying effects on the centre and the surrounding emissions, with a strong improvement in environmental quality in the centre and degradation in the surroundings (compared to the baseline), summing up to a zero total change in quality (full internalization). For the full internalization level $P=0.66$, there is a moderate increase (+4.4%) in the equilibrium level for $\lambda$ to a value of $\lambda = 0.546$. The sensitivity of the change in environmental quality in the centre and the surroundings with respect to $P$, as well as the effect for both regions in total are illustrated in Figure 3.

**5.3. Effects on location of residence and commuting**

The instrument of cordon pricing affects commuter flows in both directions i.e. flows from the centre to the outlying region and vice versa. Thus, this instrument combats the rise in commuters that has been induced by urban sprawl. As shown in Table 3, group 3 and group 4 commuters decline in numbers relative to the urban sprawl scenarios (-6.5% and -6.9%), which is compensated for by a rise in non-commuters (group 1 and group 2). Moreover, the
number of residents in the surroundings 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 the spatial planning instrument in the surroundings, we have to take account of the fact that this measure mainly affects those residents who live in the peripheral region. Remarkable are the dramatic fall in outlying residents (-15.7%) and its corresponding rise for the centre population (+15.5%). Thus, the restriction of housing in the surroundings operates strongly on the consumers’ housing decision, driving up outlying 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 surroundings).

[Table 3 about here]

5.4. Environmental impacts

Based on changes in settlement structures and commuting flows we evaluate the environmental impacts of the implemented policies. Recall that both cordon pricing and spatial planning are imposed in order to restore the baseline level of environmental quality over both regions (full internalization level). Let us have a look at the share of commuters (left panels in Figure 4) and the population per region (right panels) in each scenario again.

[Figure 4 about here]

For the two instruments we find the following. The improved environment induced by cordon pricing stems from a decrease in the number of commuters (groups 3 and 4) whose emission factors are highest. As a consequence, cordon pricing improves the level of environmental quality in both regions, with a stronger effect in the centre region; here the pollution level declines by 2.6% relative to a situation of urban sprawl. For both regions in total, emissions
are reduced by 1.5% compared to urban sprawl, thereby restoring the reference level of environmental quality (baseline). The values are reported in Table 4.

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 surroundings (i.e., a decline in group 2 and group 4 workers), via the induced rise in outlying 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 outer region (group 3 increases). For spatial planning, the pollution level thus decreases considerably in the centre (-8%), as shown in Table 4, and rises moderately in the surroundings (+3%). Taking the effects for the centre and the outlying regions together, the overall level of pollutants equals the baseline level.

[Table 4 about here]

6. Summary and conclusions

This paper attempts to explain the driving forces for urban sprawl 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 two policy instruments to address urban sprawl and its environmentally harmful implications.

The number of commuters and non-commuters determines the region-specific level of environmental quality. Since environmental quality contributes to household utility, it affects the location decision of households in the long run. If the environmental quality differs across regions, a lower environmental quality 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 for 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, compared to the baseline, larger fraction of residents located in the region with lower overall environmental impacts (the surrounding area).

In our policy analysis, we first investigate the effects of cordon pricing in order to reduce the number of interregional commuters. Second, we look at the consequences of a spatial planning instrument, in that zoning plans in the surrounding area are more stringent, i.e. reducing the effective housing supply in this region. 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.

Both instruments generally reduce urban sprawl, though they do so through different channels. Cordon pricing curbs sprawl by addressing commuters. By contrast, a planning measure is capable of reducing the degree of urban sprawl due to the consequent rise in property prices in the addressed region. Moreover, 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 effects 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. Implementing a spatial planning instrument, however, leads to similar effects for those 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 local pollutants, such as PM$_{10}$, per region. The reason is that cordon pricing most strongly curbs the total number of commuters, driving long distances with car dependent modal shares, which improves the environment. On the other hand, instruments restricting housing supply in the surroundings do so by applying to residents who commute to the centre and to those who drive long distances within the outlying region. Applying this instrument, however, significantly increases commuting from the centre to the surroundings. Hence, from a regional perspective, the pricing policy is connected to favourable emission reductions in both regions, whereas the planning measure in the outlying area has ambiguous results from an environmental perspective (with an improvement for the centre, but a degradation for the surroundings).

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, one path for future development is to fully implement an explicit modelling of mode choice, both within and across regions. This would change also the impact of the policy measures: a spatial planning measure aimed at denser living may lead 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 path is to introduce heterogeneity in environmental preferences and in skills of manufacturing workers in order to endogenise the propensity for cross-commuting. This would substitute for the Armington assumption of product differentiation in regional housing. Following these paths of modification would show how the results of the present analysis could be further developed.
References


Appendix

A.1 Stability of the symmetric equilibrium for identical regions

For the derivation of $du_M / d\lambda$ as given in equation (24), we make use of the fact that around the symmetric equilibrium, all endogenous variables are identical in both regions. Thus, the values $\lambda = \gamma_1^2$, $w_M + p_k c_M = y_M = 1$ and $p_M = 1$ hold in both the centre and the surroundings. This yields $Y = \gamma_1^2$, $G_{1-\sigma} = (1 + T_{1-\sigma}) / 2$, $Z = (1 - T_{1-\sigma}) / (2 G_{1-\sigma})$, $L_M = \gamma_2^2$ and $K_M = \gamma_2^2$; the variable $Z$ follows as an index of transport costs defined as $Z = (1 - T_{1-\sigma}) / (1 + T_{1-\sigma})$ with $0 \leq Z \leq 1$. 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 $dp_M = -dp_M^*$. Furthermore we let the environmental impact factors be equal across regions, i.e. $\mu_e = \mu_e^*$ and $\mu_h = \mu_h^*$, 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

$$du_M = d\omega + \delta dQ = G^{-\alpha} (R^{1-\beta})^{-(1-\alpha)} \Omega (dy_M - \alpha \frac{dG}{G} - dp_M (1 - \alpha)(2\beta - 1) + \delta \frac{2 dp_M e^{\frac{-\beta R_{1-\beta}(1-\beta)\mu_h}{R(R-1)^{1-\beta}}}}{(\beta(R-1)+1)^2}$$

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

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

$$dY = \alpha d\lambda + \frac{\alpha dy_M + (1 - \alpha) dp_M}{2}$$

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), $Z = 1$. 

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\[
\frac{dG}{G} = \frac{2Z}{1-\sigma} \, d\lambda + Zdy_M \quad \text{(A4)}
\]
\[
dp_H = 2dY \frac{\beta (1+R)-1}{R} \quad \text{(A5)}
\]

In order to find out whether \( \lambda = \lambda_f \) 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:

\[
\frac{du}{d\lambda} = \frac{d\omega}{d\lambda} + \delta \frac{dQ}{d\lambda} \quad \text{(A6)}
\]

\[
\frac{du}{d\lambda} \bigg|_{\lambda=0.5} = \left[ \frac{2G^{-\alpha} \left( R^{1-\beta} \right)^{(1-\alpha)} \Omega}{\sigma - 1} \right] \left[ \alpha(1 - \alpha)(\sigma - 1)\sigma V + \alpha Z(R + \sigma(\beta(1 + R)(1 - \alpha) + \alpha - 2R - 1)) + \right.
\]
\[
+ Z^2(- (1 - \alpha)(\sigma - 1)(V(\alpha \sigma + \frac{0.5}{\beta - 0.5}) + R(\sigma(1 + \alpha^2) - 1)))] +
\]
\[
+ \delta \frac{4}{(1 + (R - 1)\beta)^2} \alpha \beta \sigma \rho R(\mu_c - \mu_h)(Z^2 - 1) \left( V \frac{1 - \beta}{2(\beta - 0.5)} \right) \times
\]
\[
\frac{1}{\alpha Z R + Z^2(\sigma - 1)(- (1 - \alpha) \frac{V}{2(\beta - 0.5)} + R) + \sigma(\alpha + \beta(1 - \alpha)(1 + R) - R - 1)}
\]

where \( V \equiv 2(\beta - 0.5)(\beta(1 + R) - 1), \ Z \equiv (1 - T^{1-\sigma})/(1 + T^{1-\sigma}), \) and \( \Omega \) as defined in equation (A1).
## A.2 List of variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>manufacturing good (quantity composite)</td>
</tr>
<tr>
<td>$m(i)$</td>
<td>local demand for variety $i$</td>
</tr>
<tr>
<td>$m(j)^*$</td>
<td>demand for imported variety $j$</td>
</tr>
<tr>
<td>$H_{c,M}$</td>
<td>housing demand of manufacturing workers with residence and job location in the centre (group 1)</td>
</tr>
<tr>
<td>$H_{c,M}^*$</td>
<td>housing demand of manufacturing workers commuting to the surroundings (group 2)</td>
</tr>
<tr>
<td>$H_{s,M}$</td>
<td>housing demand of manufacturing workers with residence and job location in the surroundings (group 3)</td>
</tr>
<tr>
<td>$H_{s,M}^*$</td>
<td>housing demand of manufacturing workers commuting to the centre (group 4)</td>
</tr>
<tr>
<td>$Q$</td>
<td>environmental quality</td>
</tr>
<tr>
<td>$D$</td>
<td>environmental damage</td>
</tr>
<tr>
<td>$w_M$</td>
<td>manufacturing wage</td>
</tr>
<tr>
<td>$G$</td>
<td>price index consumption good (for one unit of $M$)</td>
</tr>
<tr>
<td>$p_s(i)$</td>
<td>consumer price of variety $i$</td>
</tr>
<tr>
<td>$p_M$</td>
<td>producer (f.o.b.) price of variety $i$</td>
</tr>
<tr>
<td>$F = \alpha / \sigma$</td>
<td>fixed labour input in manufacturing</td>
</tr>
<tr>
<td>$a_M = \rho$</td>
<td>variable labour input in manufacturing</td>
</tr>
<tr>
<td>$q_M = F \cdot \sigma$</td>
<td>manufacturing output of a single firm</td>
</tr>
<tr>
<td>$w_H$</td>
<td>housing wage</td>
</tr>
<tr>
<td>$p_H$</td>
<td>price of one unit of housing</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>share of manufacturing labour in the centre</td>
</tr>
<tr>
<td>$g_1$</td>
<td>group 1</td>
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<tr>
<td>$g_2$</td>
<td>group 2</td>
</tr>
<tr>
<td>$g_3$</td>
<td>group 3</td>
</tr>
<tr>
<td>$g_4$</td>
<td>group 4</td>
</tr>
<tr>
<td>$Y$</td>
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<td>per capita income of manufacturing workers</td>
</tr>
<tr>
<td>$\omega$</td>
<td>real income in manufacturing</td>
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<tr>
<td>$u_M$</td>
<td>per capita utility of manufacturing workers</td>
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### Table 1: Parameter values and exogenous and initial values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$0 \leq \alpha \leq 1$</td>
<td>0.8</td>
<td>expenditure share consumption good <em>(own calculation)</em></td>
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<tr>
<td>$1 - \alpha$</td>
<td>0.2</td>
<td>expenditure share housing <em>(own calculation)</em></td>
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<td>$0 &lt; \rho &lt; 1$</td>
<td>0.8</td>
<td>intensity of preference for variety <em>(Eppink and Witthagen, 2006)</em></td>
</tr>
<tr>
<td>$\sigma = 1/(1 - \rho)$</td>
<td>5</td>
<td>elasticity of substitution between varieties <em>(Eppink and Witthagen, 2006)</em></td>
</tr>
<tr>
<td>$\delta &gt; 0$</td>
<td>5000</td>
<td>intensity of environmental preferences (scaling parameter for environmental quality)</td>
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<td>$\mu_1 \geq 0$</td>
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<td>environmental damage parameter for group 1 <em>(own calculation)</em></td>
</tr>
<tr>
<td>$\mu_2 \geq 0$</td>
<td>0.44</td>
<td>environmental damage parameter for group 2 <em>(own calculation)</em></td>
</tr>
<tr>
<td>$\mu_3 \geq 0$</td>
<td>0.64</td>
<td>environmental damage parameter for group 3 <em>(own calculation)</em></td>
</tr>
<tr>
<td>$\mu_4 \geq 0$</td>
<td>0.64</td>
<td>environmental damage parameter for group 4 <em>(own calculation)</em></td>
</tr>
<tr>
<td>$\epsilon \geq 0$</td>
<td>0.5</td>
<td>Armington elasticity of substitution between home production of housing and imports <em>(assumption)</em></td>
</tr>
</tbody>
</table>

#### Exogenous and initial values

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{L}$</td>
<td>1</td>
</tr>
<tr>
<td>$L_n = (1 - \alpha)/2$</td>
<td>0.1</td>
</tr>
<tr>
<td>$L'_n = (1 - \alpha)/2$</td>
<td>0.1</td>
</tr>
<tr>
<td>$L_u$</td>
<td>0.4</td>
</tr>
<tr>
<td>$L'_u$</td>
<td>0.4</td>
</tr>
<tr>
<td>$S \geq 1$</td>
<td>1</td>
</tr>
<tr>
<td>$R \geq 1$</td>
<td>1</td>
</tr>
<tr>
<td>$P &gt; 0$</td>
<td>1</td>
</tr>
<tr>
<td>$T \geq 1$</td>
<td>1</td>
</tr>
<tr>
<td>$0 \leq r \leq 1$</td>
<td>0.25</td>
</tr>
<tr>
<td>$0 \leq r' \leq 1$</td>
<td>0.25</td>
</tr>
<tr>
<td>$0 \leq t_c \leq 1$</td>
<td>0.25</td>
</tr>
<tr>
<td>$0 \leq t_s \leq 1$</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Table 2: The population distribution for the urban sprawl scenario (and changes compared to the baseline).

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Urban Sprawl</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>non-commuters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>centre (= group 1)</td>
<td>0.388</td>
<td>0.378</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-2.6%</td>
</tr>
<tr>
<td>surroundings (= group 2)</td>
<td>0.362</td>
<td>0.353</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-2.5%</td>
</tr>
<tr>
<td><strong>commuters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to surroundings (= group 3)</td>
<td>0.119</td>
<td>0.124</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+4.2%</td>
</tr>
<tr>
<td>to centre (= group 4)</td>
<td>0.132</td>
<td>0.144</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+9.1%</td>
</tr>
<tr>
<td><strong>workforce per region</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>centre (= groups 1 + 4)</td>
<td>0.520</td>
<td>0.523</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+0.6%</td>
</tr>
<tr>
<td>surroundings (= groups 2 + 3)</td>
<td>0.480</td>
<td>0.477</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.6%</td>
</tr>
<tr>
<td><strong>residents per region</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>centre (= groups 1 + 3)</td>
<td>0.507</td>
<td>0.503</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.8%</td>
</tr>
<tr>
<td>surroundings (= groups 2 + 4)</td>
<td>0.493</td>
<td>0.497</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+0.8%</td>
</tr>
</tbody>
</table>
Table 3: The population distribution for the policy scenarios (and changes compared to the urban sprawl scenario).

<table>
<thead>
<tr>
<th></th>
<th>Urban Sprawl</th>
<th>Cordon Pricing</th>
<th>Spatial Planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-commuters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>centre (= group 1)</td>
<td>0.378</td>
<td>0.389</td>
<td>0.430</td>
</tr>
<tr>
<td></td>
<td>+2.9%</td>
<td>+13.8%</td>
<td></td>
</tr>
<tr>
<td>surroundings (= group 2)</td>
<td>0.353</td>
<td>0.362</td>
<td>0.303</td>
</tr>
<tr>
<td></td>
<td>+2.5%</td>
<td>-14.2%</td>
<td></td>
</tr>
<tr>
<td>commuters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to surroundings (= group 3)</td>
<td>0.124</td>
<td>0.116</td>
<td>0.151</td>
</tr>
<tr>
<td></td>
<td>-6.5%</td>
<td>+21.8%</td>
<td></td>
</tr>
<tr>
<td>to centre (= group 4)</td>
<td>0.144</td>
<td>0.134</td>
<td>0.116</td>
</tr>
<tr>
<td></td>
<td>-6.9%</td>
<td>-19.4%</td>
<td></td>
</tr>
<tr>
<td>workforce per region</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>centre ((\lambda)) ((=) groups 1+ 4)</td>
<td>0.523</td>
<td>0.523</td>
<td>0.546</td>
</tr>
<tr>
<td></td>
<td>+0.0%</td>
<td>+4.4%</td>
<td></td>
</tr>
<tr>
<td>surroundings (1-(\lambda)) ((=) groups 2 + 3)</td>
<td>0.477</td>
<td>0.477</td>
<td>0.454</td>
</tr>
<tr>
<td></td>
<td>+0.0%</td>
<td>-4.8%</td>
<td></td>
</tr>
<tr>
<td>residents per region</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>centre ((=) groups 1 + 3)</td>
<td>0.503</td>
<td>0.505</td>
<td>0.581</td>
</tr>
<tr>
<td></td>
<td>+0.4%</td>
<td>+15.5%</td>
<td></td>
</tr>
<tr>
<td>surroundings ((=) groups 2 + 4)</td>
<td>0.497</td>
<td>0.495</td>
<td>0.419</td>
</tr>
<tr>
<td></td>
<td>-0.4%</td>
<td>-15.7%</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Changes in local pollution for the urban sprawl scenario and the policy scenarios cordon pricing and spatial planning (compared to the baseline and the urban sprawl scenario).

<table>
<thead>
<tr>
<th></th>
<th>Urban Sprawl</th>
<th>Cordon Pricing</th>
<th>Spatial Planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>changes relative to urban sprawl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>centre</td>
<td>-2.6%</td>
<td>-8.0%</td>
<td></td>
</tr>
<tr>
<td>surroundings</td>
<td>-0.7%</td>
<td>+3.0%</td>
<td></td>
</tr>
<tr>
<td>total effect</td>
<td>-1.5%</td>
<td>-1.5%</td>
<td></td>
</tr>
<tr>
<td>changes relative to the baseline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>centre</td>
<td>+3.0%</td>
<td>+0.3%</td>
<td>-5.3%</td>
</tr>
<tr>
<td>surroundings</td>
<td>+0.6%</td>
<td>-0.2%</td>
<td>+3.5%</td>
</tr>
<tr>
<td>total effect</td>
<td>+1.5%</td>
<td>+0.0%</td>
<td>+0.0%</td>
</tr>
</tbody>
</table>
Figure 1: Difference in utility ($u - u^*$), real wage ($w - w^*$) and environmental quality ($Q - Q^*$) for different values of $\lambda$ with $S=1$, $R=1$ and $P=1$. 

Baseline
Figure 2: Sensitivity of the change in local pollution (compared to the baseline) with respect to the cordon pricing policy parameter $R$.

![Sensitivity of cordon pricing policy](image)

Figure 3: Sensitivity of the change in local pollution (compared to the baseline) with respect to the spatial planning policy parameter $P$.

![Sensitivity of spatial planning policy](image)
Figure 4: Commuting flows (group 3 to surroundings and group 4 to centre) and settlement structure (centre and outlying residents) under different scenarios.