Environmental Policy and the Collapse of the Monocentric City

Efthymia Kyriakopoulou*

Athens University of Economics and Business

Anastasios Xepapadeas†

Athens University of Economics and Business and Beijer Fellow

April 28, 2010

*Department of International and European Economic Studies, Athens University of Economics and Business, 76 Patission Str., GR104 34, Athens, Greece. Telephone: +30 210 8203354. E-mail: efik@aueb.gr

† *Corresponding author*: Department of International and European Economic Studies, Athens University of Economics and Business, 76 Patission Str., GR104 34, Athens, Greece. Telephone: +30 210 8203198. E-mail: xepapad@aueb.gr

Environmental Policy and the Collapse of the Monocentric City

Abstract

We explain the spatial concentration of economic activity, in a model of economic geography, when the cost of environmental policy - which is increasing in the concentration of pollution - acts as a centrifugal force, while positive knowledge spillovers and a site with natural cost advantage act as centripetal forces. We study the agglomeration effects caused by trade-offs between centripetal and centrifugal forces which eventually determine the distribution of economic activity across space. The rational expectations market equilibrium with spatially myopic environmental policy results either in a monocentric or in a polycentric city with the major cluster at the natural advantage site. The regulator's optimum results in a bicentric city which suggests that when environmental policy is spatially optimal, the natural advantage sites do not act as attractors of economic activity.

JEL classification: R38, Q58.

Keywords: Agglomeration, Space, Environmental policy, Natural cost advantage, Knowledge spillovers, Monocentric-bicentric city.

1 Introduction

Among the major factors explaining the emergence of industrial agglomerations are industry spillovers and the existence of locations with natural cost advantage. The first factor is one of the classic Marshallian sources of external economics and refers to the concentration of economic activity at a specific interval that is created through information or knowledge spillovers. However, Marshall (1920) also identified the second factor of natural advantage as a determinant of industry location. In particular, he (Marshall, 1920, p. 269) argued that the location decisions of industries are highly influenced by physical conditions, such as the climate, the soil, mines or quarries in nearby areas, or easy access by land or water.

Krugman (1999) identifies not only the importance of first nature advantage and Marshallian externalities in explaining agglomeration, but also the interaction between them. Thus, natural geography determines the city site in most cases. A lot of cities are created around a port so as to have easy access to the goods transported, or a lot of industries using mineral resources in the production process are located near the mines, so as to avoid the high transportation cost. One can think of many examples of this kind and the result is easily predicted: sites with "natural advantages" are more likely to attract a large number of agents and economic activity. But once the site has been chosen and the city is established, there are other forces that persist and lead to an even higher concentration of economic activity around the first nature advantage point. These are the interactions between economic agents, such as knowledge and information spillovers, economies of intra-industry specialization, or labor market economies. As Krugman (1999) points out, that kind of forces has been proved to be stronger, after natural geography has determined the agglomeration point.

The first nature advantage and the interactions between economic agents have also been studied empirically, as they provide two of the most significant forces explaining the clustering of economic activity. Ellison and Glaeser (1999) show that one-fifth of this clustering can be attributed to observable natural advantages such as resource and labor-market natural advantages. LaFountain (2005), studying the reasons that lead different industries to locate in different places, finds strong evidence supporting the location of specific firms around natural advantage sites. Roos (2005) shows that more than one-third of agglomeration in Germany can be attributed to natural features and agglomeration economies. Rosenthal and Strange (2001, 2004) find empirical evidence regarding the significance of natural advantages and knowledge spillovers as determinants of agglomeration.

The theoretical and empirical literature analyzed above implies that first nature advantage sites will attract a high number of industries. When certain industries decide to locate around that site, then the need for other industries to locate nearby so as to benefit from information and knowledge spillovers is even stronger. As a consequence, there is always a higher concentration of economic activity around first nature advantages sites. The use of the examples of New York or Mexico City in describing the influence of those two forces is common in the literature of New Economic Geography. However, high industrial concentration is sometimes associated with certain negative externalities, such as pollution or congestion, which implies that there may be a better equilibrium than the one obtained by market equilibrium. In that case, as Krugman (1999, p. 159) argues, government intervention and enforcement of the suitable policy are required, and this may lead to a situation different from the one corresponding to unregulated equilibrium.

In this paper we study the geographical concentration of industrial activity by combining the agglomeration forces of knowledge spillovers and the existence of a location with natural cost advantage, with the fact that the industrial activity is associated with emissions of pollutants. Emissions cause damages and this creates the need to regulate them by implementing environmental policy. In our model, environmental policy takes the form of emission taxes which are different among locations and tend to be higher in sites where the concentration of pollutants is relatively higher. Furthermore, the concentration of pollutants in a given site is determined not only by emissions generated in that site, but also by emissions generated in nearby locations, since in our model emissions diffuse in space.

Thus, while knowledge spillovers and natural cost advantage act as centripetal forces which promote agglomeration and clustering of industrial activity, environmental policy acts as a centrifugal force, since agglomeration tends to increase the concentration of pollutants and consequently emission taxes, which represents a higher cost to the industry.[1] Our intention is to examine how the assumption of pollution which implies the enforcement of environmental policy will affect the high concentration of economic activity that results from knowledge spillovers and natural advantage. The question we try to answer is whether environmental policy can refute the prediction (e.g. Krugman, 1999) that agglomeration of economic activity will emerge around a first nature advantage site as a result of the interaction between knowledge spillovers and natural cost advantage forces.[2] To the best of our knowledge, the assumption of pollution diffusing in space and the implementation of environmental policy have never been combined with the two important determinants of agglomeration studied here, i.e. spatial inhomogeneity in the form of an inherent advantage and production externalities.

In our model the spatial distribution of industrial activity, in a given finite spatial domain, is determined under two different assumptions regarding the implementation of environmental policy: a "spatially myopic" policy and a "spatially optimal" policy. When policy is myopic, the emission tax in a given location does not take into account the impact that emissions in this same location have on aggregate pollution and associated environmental damages in nearby locations due to spatial diffusion of emissions. Myopic policy is associated with the concept of a rational expectations equilibrium (REE) where profit maximizing firms in each location treat knowledge spillovers and the concentration of pollution as fixed parameters. A spatially optimal or simply optimal policy is determined in the context of the regulator's optimum. In this case, emission taxes in a given location account for the impact of local emissions on pollution concentration and environmental damages in neighboring locations. We model knowledge spillovers and

[1] The argument that environmental regulations impede the agglomeration of economic activity has been established by the empirical literature. Henderson (1996) shows that air quality regulation leads pollution industries to spread out, moving from polluted to cleaner areas. Greenstone (2002) finds that environmental regulation restricts industrial activity.

[2] Environmental issues have not been studied a lot in new economic geography models. Some exceptions are the recent works of Lange and Quaas (2007) and van Marrewijk (2005) who study the effect of pollution on agglomeration assuming local pollution. Arnott et al. (2008) assume non-local pollution while investigating the role of space in the control of pollution externalities.

spatial diffusion of emissions by symmetric exponentially declining integral kernels, while natural cost advantage is modeled by iceberg type input costs which increase with the distance from the natural advantage location.

Our results, based on numerical simulations, indicate that when the centripetal forces of knowledge spillovers and natural cost advantage for a location are combined with the centrifugal force of spatially differentiated environmental policy, then in the REE the main cluster of economic activity is always observed around the natural advantage location as suggested by the literature.[3] However, when environmental policy is optimal, there is no agglomeration on the location with the natural advantage but instead industrial activity is concentrated in two clusters forming a bicentric city. As our numerical simulations show, the result of a repelling natural cost advantage location is quite robust in parameter changes, as well as in the placement of the natural cost advantage location in different sites of our spatial domain.

The rest of the paper is organized as follows. In Section 2, we present the model and its mathematical structure, Section 3 determines the regulator's optimum, while in Section 4, we derive optimal spatial policies. In Section 5, we present our numerical experiments and compare the different output distributions corresponding to the REE and the optimal solutions. The final section concludes.

2 Rational Expectations Equilibrium under Centripetal and Centrifugal Forces

We consider a finite spatial domain, which could be interpreted as a single city or a region located on a line of length S. Thus 0 and S can be thought of as the western and eastern borders of the city, which is part of a large economy. In the city, there is a large number of small, identical firms that produce a single good. There are also workers who live at their workplaces and take no location decisions. The production process is characterized by

[3] Although we prove existence and uniqueness of the REE and the regulator's optimum, specific results are obtained by simulations due to the well-known intractability of economic geography models that prevents closed form solutions.

externalities in the form of positive knowledge spillovers.[4] This means that firms benefit from locating near each other and the total advantage they have depends on the amount of labor used in nearby areas and on the distance between them.

We assume that there is an inherent cost advantage in a specific site $\bar{r} \in [0, S]$ which can take various interpretations. For example, $\bar{r}$ could be a port, a natural resource extraction site, or an area where cheap energy can be found. In this case, firms that use inputs which can be obtained more cheaply if they locate near the cost advantage site, would compete to locate near this site. Thus location $\bar{r}$ has a natural cost advantage. In this paper we assume, without loss of generality, that at point $\bar{r}$ there is a port, which is used to import machinery. Machinery arrives at the port at an exogenous price that includes cost, insurance and freight (cif price). The transportation of machinery inside the city is costly. Thus if firms decide to locate close to the port, they will pay very small transportation costs for the machinery. At all other points, the transportation cost will add an additional cost to the production process. Finally, we treat emissions as an input in the production process.[5]

We study the equilibrium spatial distribution of production in order to determine the distribution of economic activity over sites $r \in [0, S]$.[6] All firms produce the same traded good using labor, machinery, emissions and land. The good is sold around the world at a competitive price assuming no transportation cost.[7] Production *per unit of land* at

[4] There are a lot of empirical studies that confirm the role of knowledge spillovers in the location decisions of firms. Keller (2002) finds that technological knowledge spillovers are significantly local and their benefits decline with distance. Bottazzi and Peri (2003) prove that knowledge spillovers resulting from patent applications are very localised and positively affect regions within a distance of 300 km. Carlino et al. (2007) provide evidence on patent intensity for metropolitan areas in the US and conclude that it is affected by employment density.

[5] The concept of emissions / pollution as an input in the production function was first introduced by Brock (1977) and later used by other authors, eg. Jouvet et al. (2005), Rauscher (1994), Stokey (1998), Tahvonen and Kuuluvainen (1993), Xepapadeas (2005). The idea behind this assumption is that techniques of production are less costly in terms of capital input (machinery in our case) if more emissions are allowed - a situation which is observed in the real world. In other words, if we use polluting techniques, we can reduce the total cost of production.

[6] Land is owned by landlords who play no role in our analysis.

[7] This assumption is used by Lucas and Rossi-Hansberg (2002). Alternatively, we could assume that the good is exported from the port to the larger economy at a fixed (competitive) price, but the transportation to the port is costly. In that case, the transportation cost of the output would push economic activity to concentrate around the port and would have the same implications as the transportation cost of the machinery input.

location $r \in [0, S]$ is given by:

$$q(r) = e^{\gamma z(r)} L(r)^a K(r)^b E(r)^c \tag{1}$$

where q is the output, L is the labor input, K is the machinery input, E is the amount of emissions used in production and z is the production externality, which depends on how many workers are employed at all locations and represents positive knowledge spillovers[8]

$$z(r) = \delta \int_0^S e^{-\delta(r-s)^2} \ln(L(s)) \, ds \tag{2}$$

The function $k(r, s) = e^{-\delta(r-s)^2}$ is called a kernel. The production externality is a positive function of labor employed in all areas and is assumed to decay exponentially at a rate δ with the distance between r and s. A high δ indicates that only labor in nearby areas affects production positively. In other words, the higher δ is, the more profitable it is for firms to locate near each other. When the production externality is strong, each firm chooses to locate where all other firms are located. In terms of agglomeration economics, the production externality is a *centripetal* force, i.e. a force that promotes the spatial concentration of economic activity.

As already stated, point $\bar{r}$ has a natural cost advantage over other possible locations. If the price of machinery at $\bar{r}$ is p_K, then iceberg transportation costs imply that the price at location r can be written as $p_K(r) = p_K \; e^{\beta(r-\bar{r})^2}$. In other words, if one unit of machinery is transported from $\bar{r}$ to r, only a fraction $e^{-\beta(r-\bar{r})^2}$ reaches r.[9] So β is the transportation cost per square unit of distance, which is assumed to be positive and finite. It is obvious that the total transportation cost of machinery increases with distance.[10]

[8] This kind of external effects is used by Lucas (2001) and by Lucas and Rossi-Hansberg (2002) - with a different structure - and is consistent with Fujita and Thisse's (2002) analysis. The idea is that workers at a spatial point benefit from labor in nearby areas and thus, the distance between firms determines the production of ideas and the productivity of firms in a given region.

[9] For a detailed analysis of "iceberg costs", see Fujita et al. (1999) and Fujita and Thisse (2002). Conceptually, with the "iceberg" forms, we assume that a fraction of the good transported melts away or evaporates in transit.

[10] We can use another formulation of iceberg transportation cost, $p_K(r) = p_K \; e^{\beta|r-\bar{r}|}$ instead of $p_K(r) = p_K \; e^{\beta(r-\bar{r})^2}$, without changing the conclusions of the analysis.

Thus firms have an incentive to locate near point $\bar{r}$ to avoid a higher transportation cost. Like knowledge spillovers, the transportation cost is a *centripetal* force.

The emissions used in the production process damage the environment. The damage (D) at each spatial point is a function of the concentration of pollution (X) at the same point

$$D(r) = X(r)^{\phi} \tag{3}$$

where $\phi \geq 1,\ \ D'(X) > 0,\ \ D''(X) \geq 0,$ and the marginal damage function is:

$$MD(r) = \phi\ X(r)^{\phi-1} \tag{4}$$

Each firm has to pay a "price" or a tax for each unit of emissions it generates. This tax τ is a function of the marginal damage (MD):

$$\tau(r) = \theta\ MD(r) \tag{5}$$

where $0 \leq \theta \leq 1$, and $\theta = 1$ means that the full marginal damage at point r is charged as a tax. In other words, each firm pays an amount of money for the emissions used in the production of the output, but the per unit tax depends not only on its own emissions, but also on the concentration of pollution at the spatial point where it decides to locate. The tax function can be written as:

$$\tau(r) = \theta\ \phi\ X(r)^{\phi-1} = \psi\ X(r)^{\phi-1} \tag{6}$$

where $\psi = \theta\ \phi,\ \ \tau'(X) > 0,\ \ \tau''(X) \geq 0.$

When solving our model, we use the logarithm of the tax function, thus:

$$\ln \tau(r) = \ln \psi + (\phi - 1)\ \ln X(r) \tag{7}$$

where

$$\ln X(r) = \int_0^S e^{-\zeta(r-s)^2} \ln(E(s))\ ds \tag{8}$$

Equation (8) implies that aggregate pollution (X) at a point r is a weighted average of the emissions generated in nearby locations, with kernel $k(r,s) = e^{-\zeta(r-s)^2}$. This aims at capturing the movement of emissions in nearby places. A high ζ indicates that only nearby emissions affect the concentration of pollution at point r. In the real world, the value of ζ depends on weather conditions and on natural landscape. As we have assumed that the only dissimilarity in our land is the existence of a port, we assume that ζ is influenced only by weather conditions. Specifically, if wind currents are strong, ζ takes a low value and areas at a long distance from r are polluted by emissions generated at r. As ζ increases, the concentration of emissions in certain areas does not pollute other areas so much.

Thus the cost of environmental policy, $\tau(X(r))$, increases the total production cost for the firms. The extra amount of money that a firm pays in the form of taxation depends on the concentration of pollution at the point where it has decided to locate. To put it differently, the higher the concentration of production in an interval $[s_1, s_2] \subset [0, S]$, the higher the environmental related costs that firms will have to pay. Thus, the environmental policy is a *centrifugal* force, i.e. a force that impedes spatial concentration of economic activity.

Let w be the wage rate, which is the same across sites, and let p be the competitive price of output.[11] A firm located at r chooses labor, machinery and emissions to maximize its profits. Thus, the *profit per unit of land*, $\hat{Q}$, at location r, is given by:

$$\hat{Q}(r) = \max_{L,K,E} \; p\, e^{\gamma z(r)} L(r)^a K(r)^b E(r)^c - wL(r) - p_K\, e^{\beta(r-\bar{r})^2} K(r) - \tau(r)\, E(r) \tag{9}$$

A firm located at site r treats the production externality $z(r)$ and the concentration of pollution $X(r)$ as exogenous parameters z^e and X^e respectively. Assuming $X(r)$ is exogenous to the firm implies that the tax $\tau(r)$ is treated by the firms as a fixed parameter

[11] Real wages are constant which means that the marginal product of labor, as defined by the FOC (10a) is constant across locations. This assumption is also used by Rossi-Hansberg (2005) who investigates the spatial distribution of economic activity and the associated trade patterns. In Section 3, where we study the optimal distribution of economic activity, the marginal product of labor differs across sites (see equation (16a) below).

at each r. Then, the first order necessary conditions (FONC) for profit maximization are:

$$pa\ e^{\gamma z(r)} L(r)^{a-1} K(r)^{b} E(r)^{c} = w \tag{10a}$$

$$pb\ e^{\gamma z(r)} L(r)^{a} K(r)^{b-1} E(r)^{c} = p_K\ e^{\beta(r-\overline{r})^2} \tag{10b}$$

$$pc\ e^{\gamma z(r)} L(r)^{a} K(r)^{b} E(r)^{c-1} = \tau(r) \tag{10c}$$

where $\tau(r) = \psi\ X(r)^{\phi-1}$. Setting $z^e = z(r)$, $X^e = X(r)$, the FONC define a *rational expectations equilibrium spatial distribution* of labor, machinery and emissions at each point $r \in [0, S]$. After taking logs on both sides and doing some transformations, which are described in Appendix A, the FONC result in a system of second kind Fredholm integral equations with symmetric kernels:

$$\begin{aligned}
\tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2} y(s)ds + \tfrac{c(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}\varepsilon(s)ds + g_1(r) &= y(r) \\
\tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2} y(s)ds + \tfrac{c(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}\varepsilon(s)ds + g_2(r) &= x(r) \\
\tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2} y(s)ds + \tfrac{(1-a-b)(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}\varepsilon(s)ds + g_3(r) &= \varepsilon(r)
\end{aligned} \tag{11}$$

where $y(r) = \ln L(r)$, $x(r) = \ln K(r)$, $\varepsilon(r) = \ln E(r)$ and $g_1(r)$, $g_2(r)$, $g_3(r)$ are some known functions.

Proposition 1 . *Assume that: (i) the kernel $k(r,s)$ defined on $[0, 2\pi] \times [0, 2\pi]$ is an L_2-kernel which generates the compact operator W, defined as $(W\phi)(r) = \int_a^b k(r,s)\,\phi(s)\,ds$, $a \leq s \leq b$, (ii) $1-a-b-c$ is not an eigenvalue of W, and (iii) G is a square integrable function, then a unique solution determining the rational expectations equilibrium distribution of inputs and output exists.*

The proof of existence and uniqueness of the REE is presented in the following steps:[12]

- A function $k(r,s)$ defined on $[a,b] \times [a,b]$ is an L_2-kernel if it has the property that $\int_a^b \int_a^b |k(r,s)|^2\, drds < \infty$.

[12]See Moiseiwitsch (2005) for more detailed definitions.

The kernels of our model have the following formulation: $e^{-\xi\ (r-s)^2}$ with $\xi = \delta,\ \zeta$ (positive numbers) and are defined on $[0, 2\pi] \times [0, 2\pi]$.

We need to prove that $\int_0^{2\pi} \int_0^{2\pi} \left| e^{-\xi\ (r-s)^2} \right|^2 drds < \infty$.

Rewriting the left part of the inequality, we get: $\int_0^{2\pi} \int_0^{2\pi} \left| \frac{1}{e^{\xi\ (r-s)^2}} \right|^2 drds$.

The term $\frac{1}{e^{\xi\ (r-s)^2}}$ takes its highest value when $e^{\xi\ (r-s)^2}$ is very small. But the lowest value of $e^{\xi\ (r-s)^2}$ is obtained when either $\xi = 0$ or $r = s$, and in that case $e^0 = 1$. So $0 < \left| \frac{1}{e^{\xi\ (r-s)^2}} \right| < 1$. When $\left| \frac{1}{e^{\xi\ (r-s)^2}} \right| = 1$, then $\int_0^{2\pi} \int_0^{2\pi} \left| \frac{1}{e^{\xi\ (r-s)^2}} \right|^2 drds = 4\ \pi^2 < \infty$. Thus the kernels of our system are L_2-kernels.

- If $k\,(r, s)$ is an L_2- kernel, the integral operator

$$(W\phi)\,(r) = \int_a^b k\,(r, s)\,\phi\,(s)\,ds\ , a \leq s \leq b$$

that it generates is bounded and

$$\|W\| \leq \left\{ \int_a^b \int_a^b |k\,(r, s)|^2\,drds \right\}^{\frac{1}{2}}$$

So, in our model the upper bound of the norm of the operator generated by the L_2-kernel is $\|W\| \leq \left\{ \int_a^b \int_a^b |k\,(r, s)|^2\,drds \right\}^{\frac{1}{2}} = \left\{ \int_0^{2\pi} \int_0^{2\pi} \left| \frac{1}{e^{i\ (r-s)^2}} \right|^2 drds \right\}^{\frac{1}{2}} \leq 2\pi$.

- If $k\,(r, s)$ is an L_2- kernel and W is a bounded operator generated by k, then W is a compact operator.

- If $k\,(r, s)$ is an L_2-kernel and generates a compact operator W, then the integral equation :

$$Y - \left(\tfrac{1}{1-a-b-c}\right) W\ Y = G \tag{12}$$

has a *unique* solution for all square integrable functions G, if $(1 - a - b - c)$ is not an eigenvalue of W (Moiseiwitsch, 2005). If $(1 - a - b - c)$ is not an eigenvalue of W, then $\left(I - \frac{1}{1-a-b-c} W\right)$ is invertible.

- As we show in Appendix C, the system (11) can be transformed into a second kind

Fredholm Integral equation of the form (12). Thus a unique REE distribution of inputs and output exists.□

To solve the system (11) numerically, for the REE, we use a modified Taylor-series expansion method (Maleknejad et al., 2006). More precisely, a Taylor-series expansion can be made for the solutions $y(s)$ and $\varepsilon(s)$ in the integrals of the system (11). We use the first two terms of the Taylor-series expansion (as an approximation for $y(s)$ and $\varepsilon(s)$) and substitute them into the integrals of (11). After some substitutions, we end up with a linear system of ordinary differential equations of the form:

$$\theta_{11}(r)\ y(r) + \theta_{12}(r)\ y'(r) + \theta_{13}\ y''(r) + \sigma_{11}\ \varepsilon(r) + \sigma_{12}\ \varepsilon'(r) + \sigma_{13}\ \varepsilon''(r) = g_1(r) \quad (13)$$

$$x(r) + \theta_{21}(r)\ y(r) + \theta_{22}(r)\ y'(r) + \theta_{23}\ y''(r) + \sigma_{21}\ \varepsilon(r) + \sigma_{22}\ \varepsilon'(r) + \sigma_{23}\ \varepsilon''(r) = g_2(r)$$

$$\theta_{31}(r)\ y(r) + \theta_{32}(r)\ y'(r) + \theta_{33}\ y''(r) + \sigma_{31}\ \varepsilon(r) + \sigma_{32}\ \varepsilon'(r) + \sigma_{33}\ \varepsilon''(r) = g_3(r)$$

In order to solve the linear system (13), we need an appropriate number of boundary conditions. We construct them and then we obtain a linear system of three algebraic equations that can be solved numerically.

The maximized value of the firm's profits $\hat{Q}(r)$ is also the land-rent per unit of land that a firm would be willing to pay to operate with these cost and productivity parameters at location r. Since the decision problem at each location is completely determined by the technology level z, the wage rate w, the price of machinery p_K , the output price p and the concentration of pollution X, the FONC of the maximization problem give us the REE values of labor, machinery and emissions used at each location: $L = \hat{L}(z, w, p_K, p, X)$, $K = \hat{K}(z, w, p_K, p, X)$ and $E = \hat{E}(z, w, p_K, p, X)$. Finally, the equilibrium distribution of output is given by: $q = \hat{q}(z, w, p_K, p, X)$.

3 The Regulator's Optimum

After having solved for the REE, we study the optimal solution by assuming the existence of a regulator who takes all the location decisions. The regulator's objective is to maximize the total value of land in the city, which implies maximization of the profits net of pollution damages across the spatial domain. So the regulator's problem is:

$$\max_{L,K,E}\int_0^S \left[p\ e^{\gamma z(r)}L(r)^a K(r)^b E(r)^c - wL(r) - p_K\ e^{\beta(r-\overline{r})^2}K(r) - D(r)\right] dr \qquad (14)$$

Substituting (3) for the damage function, inside the integral, we get:

$$\max_{L,K,E}\int_0^S \left[p\ e^{\gamma z(r)}L(r)^a K(r)^b E(r)^c - wL(r) - p_K\ e^{\beta(r-\overline{r})^2}K(r) - X(r)^{\phi}\right] dr \qquad (15)$$

The FONC for the optimum are:

$$ape^{\gamma z(r)}L(r)^{a-1}K(r)^b E(r)^c + pe^{\gamma z(r)}L(r)^a K(r)^b E(r)^c \gamma\frac{\partial z(r)}{\partial L(r)} = w \qquad (16a)$$

$$p\ b\ e^{\gamma z(r)}L(r)^a K(r)^{b-1}E(r)^c = p_K\ e^{\beta(r-\overline{r})^2} \qquad (16b)$$

$$cp\ e^{\gamma z}L(r)^a K(r)^b E(r)^{c-1} - \phi X(r)^{\phi-1}\frac{\partial X(r)}{\partial E(r)} = 0 \qquad (16c)$$

Comparing the FONC for the optimum to those for the REE, we notice some differences. First, the FONC (16a) with respect to $L(r)$ contains one extra term - the second term on the left-hand side. That is, the regulator, when choosing $L(r)$, takes into account the positive impact of $L(r)$ on the production of all other sites, through knowledge spillovers. So, increasing labor at r has two effects: it increases output in the standard way, but it increases the positive externalities at all other sites as well. In the same way, labor increases at other sites increase the externality in r. This externality is now taken into account, while the firm, maximizing its own profits, considered the externality as a fixed parameter.[13]

The second difference between the optimum and the REE concerns the FONC with respect to $E(r)$, i.e. equation (16c). The first term on the left-hand side is the marginal product of emissions, which is the same as the FONC of the REE. The difference is in the second term, which shows how changes in the value of emissions at r affect the

[13] See Appendix B.

concentration of pollution, not only at r but also at all other sites. This damage, which is caused by the aggregate pollution in our spatial economy and is altered every time emissions increase or decrease, is now taken into account by the regulator.

After making some transformations, we end up with the following system of second kind Fredholm integral equations with symmetric kernels:[14]

$$\phi \int_0^S e^{-\zeta(r-s)^2} \varepsilon(s) ds + g_1^*(r) = y(r) \tag{17a}$$

$$\phi \int_0^S e^{-\zeta(r-s)^2} \varepsilon(s) ds + g_2^*(r) = x(r) \tag{17b}$$

$$-\frac{\gamma\delta}{c} \int_0^S e^{-\delta(r-s)^2} y(s) ds + \frac{(1-a-b)\phi}{c} \int_0^S e^{-\zeta(r-s)^2} \varepsilon(s) ds + g_3^*(r) = \varepsilon(r) \tag{17c}$$

where $y(r) = \ln L(r)$, $x(r) = \ln K(r)$, $\varepsilon(r) = \ln E(r)$ and $g_1^*(r)$, $g_2^*(r)$, $g_3^*(r)$ are some known functions. The existence and the uniqueness of the solution can be proved following the same steps which were presented in Section 2. To determine a numerical solution of the problem, we follow the same method of Taylor-series expansion used in the REE case. This approach provides an accurate approximate solution of the integral system as demonstrated by some numerical examples in Section 5.

4 Optimal Policy Issues

The differences between the REE and the regulator's optimum give us some intuition about the design of optimal policies. These differences come from the fact that the production externality $z(r)$ and the concentration of pollution $X(r)$ are taken as fixed parameters in the case of REE, while the regulator takes them into account. Specifically, comparing equations (10a) and (10c) with (16a) and (16c) respectively, we observe that the latter equations have one extra term each. Thus the FONC with respect to $L(r)$ for the REE equates the marginal product of labor with the given real wage rate $MP_L = \frac{w}{p} = \bar{\omega}$, while the same condition for the optimum is given by $MP_L + q\ z'(L) = \bar{\omega}$. The design of optimal policy in that case is determined by the extra term, $q\ z'(L)$. So setting

[14]The analytical solution for the regulator's optimum is available in the Internet version of the paper.

$v^*(r) = q\ z'(L) = e^{\gamma z(r)} L(r)^a K(r)^b E(r)^c \gamma \frac{\partial z(r)}{\partial L(r)}$, the real wage rate, at the optimum, is equal to $\bar{\omega} = v^*(r) + MP_L$.[15] Conceptually, the term $v^*(r)$ takes into account the changes in the knowledge spillovers across space, when a firm employs more or fewer workers. The function $v^*(r)$ can also be considered as a subsidy that is given to firms. In that way, firms will have a lower labor cost, $\bar{\omega} - v^*(r)$, employ more labor, benefit from the higher knowledge spillovers and produce more output.

Probably more interesting is the design of optimal environmental policy. When environmental policy is spatially myopic, the profit maximizing firm equates the value of the marginal product of emissions with the tax imposed on each unit of emissions used in the production process, $p\ MP_E = \tau(r) = \phi\ X(r)^{\phi-1}$. The optimizing regulator however equates the value of the marginal product of emissions with the marginal damage of emissions, $p\ MP_E = MD_E$. There is a difference between the $MD_E = \phi X(r)^{\phi-1} \frac{\partial X(r)}{\partial E(r)}$ and the tax function $\tau(r) = \phi\ X(r)^{\phi-1}$ created by the term $\frac{\partial X(r)}{\partial E(r)}$.[16] This term shows that when a firm increases (decreases) the amount of emissions used in the production process, the concentration of pollution increases (decreases) at all spatial points as well. On the other hand, in the REE case, each firm decides about the amount of the emissions used as an input, taking the concentration of pollution across space as given without accounting for the fact that its own emissions at r affect the aggregate pollution in other areas. Thus, the designer of optimal environmental policy has to consider the extra damage caused at all spatial points by the emissions generated at r. As a result, the optimal tax function has to satisfy $\tau^*(r) = MD_E = \phi X(r)^{\phi-1} \frac{\partial X(r)}{\partial E(r)}$ and firms, under optimal environmental policy, should equate $p\ MP_E = \tau^*(r)$. Thus, in the spatial model, a tax equal to full marginal damages at the REE, as defined in (5) with $\theta = 1$, does not mean full internalization of the social cost as it is usually understood in environmental economics without spatial considerations. This is because setting $\tau(r) = \ \phi\ X(r)^{\phi-1}$ ignores this spatial externality which is captured by the term $\frac{\partial X(r)}{\partial E(r)}$. We will refer to setting the emission tax at $\tau(r)$ as the myopic internalization and setting it at $\tau^*(r)$ as the optimal internalization. Finally,

[15] The term $\frac{\partial z(r)}{\partial L(r)}$ is defined in Appendix B.

[16] We assume here that taxation at the REE charges the full marginal damage caused by the concentration of pollution at a specific site, so $\theta = 1$ and $\psi = \phi$. The term $\frac{\partial X(r)}{\partial E(r)}$ is defined in Appendix B.

imposing the optimal policy rules, $v^*(r)$ and $\tau^*(r)$, the REE can reproduce the optimum.

The enforcement of the optimal taxation, $\tau^*(r)$, implies the implementation of a different tax at each spatial point. This could be regarded as a taxation scheme which might be difficult to implement in real conditions. For this reason, based on the optimal taxation analyzed above, the regulator could enforce zoning taxation. In that case, we would have areas or zones with a flat environmental tax. More specifically, in the areas with high concentration of economic activity, which suffer from serious pollution problems, the environmental tax will be high, but constant. Thus, in the interval $[s_1, s_2] \subset S$, the optimal environmental tax (per unit of land) will be $ztax^* = \frac{1}{s_2 - s_1} \int_{s_1}^{s_2} \tau^*(s)\ ds$.

The regulator, in order to implement the efficient allocation as an equilibrium, uses the two instruments analyzed above: the subsidy $v^*(r)$ and the environmental tax $\tau^*(r)$. As far as the subsidy is concerned, the regulator subsidizes labor cost, so as to encourage firms to employ more workers in order to internalize knowledge spillovers. The total amount of money to be spent is equal to $\int_0^S v^*(s)\ L(s)\ ds$. In a similar way, the aggregate amount of money the regulator receives from the enforcement of the optimal environmental tax is $\int_0^S \tau^*(s)\ E(s)\ ds$. It's easy to predict that the tax revenues and the subsidy expenditures will not equal one another in most cases. However, if at the optimum a balanced-budget is required, then in cases where the expenditures are greater than the revenues, or $\int_0^S v^*(s)\ L(s)\ ds > \int_0^S \tau^*(s)\ E(s)\ ds$, the regulator could impose a lump-sum tax on land owners. Then, the tax per unit of land would be equal to $\overline{tax} = \frac{1}{S} \int_0^S [v^*(s)\ L(s) - \tau^*(s)\ E(s)]\ ds$. In the opposite case, where the revenues exceed the expenditures, or $\int_0^S \tau^*(s)\ E(s)\ ds > \int_0^S v^*(s)\ L(s)\ ds$, the regulator could give a lump-sum subsidy to firms.[17] The subsidy per unit of land would satisfy $\overline{sub} = \frac{1}{S} \int_0^S [\tau^*(s)\ E(s) - v^*(s)\ L(s)]\ ds$.

[17] In order to receive this financial support, the firms could for example be obliged to finance R&D in pollution control and clean production processes.

5 Numerical Experiments

The objective of this section is to predict where the economic activity will finally be concentrated under the agglomeration forces of our model. By assigning numerical values to the parameters, we can predict both the REE and the optimal spatial patterns of output in our spatial domain, which are implied by the models in Sections 2 and 3. The spatial distributions of output, labor, machinery and emissions, obtained by using the Taylor-series expansion approach, will determine the location of firms both at the REE and the regulator's optimum and will characterize the optimal spatial policies. Having in mind that we should exercise caution in interpreting simulations, our intention is to study how changes in some key parameters describing the agglomeration forces under study alter the spatial distribution of economic activity.

In our simulations the numerical values for the parameters are set as follows: The production elasticity of labor, machinery and emissions is set at $\alpha = 0.6$, $b = 0.25$, and $c = 0.05$, respectively. Thus the implied production elasticity of land is 0.1. The length of the spatial domain, or our city, is $S = 2\pi$. In the business sector analyzed here, we consider wages ($w = 1$) and the price of machinery ($p_K = 1$) as given and the same is assumed for the price of output which is set at $p = 10$. We set a reasonable value for γ, at 0.01.[18] We also assume that there is a port, the natural advantage site, located at the point $\bar{r} = \pi$. We set $\phi = 1.5$ which implies an increasing and convex damage function. Finally, the ζ parameter, which shows how much emissions generated at site r affect the concentration of pollution in nearby areas, is set at 0.5.[19] When studying possible spatial structures, we hold the above parameters constant and vary the agglomeration parameters which are the "strength" of knowledge spillovers δ, transportation cost β, and the ψ which indicates the stringency of the spatially myopic environmental policy. We also change the location of the natural advantage site ($\bar{r}$), to show that our conclusions

[18]This value of γ is low enough to ensure that the "no black hole" assumption, described in Fujita et al. (1999), holds.

[19]This value of ζ was chosen so that the emissions generated at the city centre ($\bar{r} = \pi$) have a negligible effect on the aggregate level of pollution at the two boundary points ($r = 0,\ 2\pi$). When we study the effect of taxation on the spatial structure, we will give one more value to ζ in order to show how, under the assumption of "more localized" pollution, the environmental policy changes the concentration of economic activity.

still hold.

As a benchmark case, we determine the distribution of economic activity under no agglomeration forces, i.e. $\gamma = 0,\ \delta = 0,\ \beta = 0, \zeta = 0, \psi = 0$. This means that there is no production externality, no transportation cost for machinery and no environmental policy. In other words, a firm doesn't benefit at all from nearby firms, doesn't pay anything for the emissions used in production, and the per unit cost of machinery is the same at all locations. As expected the spatial distribution of production is uniform over the spatial domain and firms have no incentives to locate at any spatial point of our economy (figure 1).

5.1 *Knowledge Spillovers*

Figure 2 presents the distribution of economic activity, in terms of the spatial distribution of output, resulting from δ values of 1, 2 and 3, for both low, $\beta = 0.045$, and high, $\beta = 0.075$, transportation costs.[20] The higher δ is, the more profitable it is for firms to locate near each other, so as to benefit from positive knowledge spillovers. In other words, the centripetal force of production externality is stronger when δ is high, and as a result, economic activity is more concentrated at certain sites. Environmental policy, when applied, is assumed to be stringent so that the marginal damage caused by the concentration of emissions is fully internalized ($\psi = 1.5$), but spatially myopic.

Figures 2a and 2b present the REE under the stringent environmental policy. When β and δ are low, the distribution of production is approximately uniform. When δ increases, there are two effects: first, spillovers affect the output more and the production increases at each site; and second, there are more incentives for agglomerations because benefits decline faster with distance. But, to produce more output, firms use more emissions and the concentration of pollution increases at each point. When the concentration of pollution is very high, the price of emissions is high too. So when firms decide where to locate, they take into account the centripetal force of strong knowledge spillovers and the centrifugal force of strict environmental policy. The trade-off between these two opposing

[20]These δ values are consistent with other numerical experiments based on models with similar formulation of knowledge spillovers. For example, see Lucas (2001).

forces forms the three peaks we observe in case $\delta = 3$ (solid line in figures 2a, 2b). This conclusion holds for low and high transportation cost (figures 2a, 2b). The impact of higher transportation cost is to decrease the concentration of economic activity in areas near the boundaries. Thus the two peaks near the boundaries are lower when β increases from 0.045 to 0.075. However, the central peak is higher relative to the boundary ones as the transportation cost around the city centre is low in every case.

Figures 2c and 2d present the REE without environmental considerations. In this case, firms do not have to pay a price or a "tax" for the emissions generated during the production process. The economic activity is now concentrated around the city centre, because of the two centripetal forces: the transportation cost and the knowledge spillovers. Stronger knowledge spillovers lead to a higher clustering of economic activity at the city centre. The use of fixed land as a production factor, however, deters economic activity from concentrating entirely at the city centre.[21] The absence of environmental policy induces the formation of a unique peak and a monocentric city. This is the very well-known result that has been explained by Krugman (1999) and verified in the empirical literature: there is always a high concentration of economic activity around natural advantage sites which is reinforced by the existence of knowledge spillovers.

Figures 2e and 2f show the optimal distribution of economic activity under optimal environmental policy. As stated above, the regulator takes into account how labor in one area benefits from labor in nearby areas and how emissions in one area affect the concentration of pollution in other areas. In this way, the regulator internalizes the production externality and the damage caused by the use of emissions in the production process. The result is the formation of two peaks at the points $r = \frac{\pi}{2}, \frac{3\pi}{2}$, from the origin of the spatial domain $[0, S]$ which is point 0.[22] Thus, a bicentric city emerges

[21]The immobility of land that acts as a centrifugal force is a common argument in new economic geography models. See, for example, Lucas and Rossi-Hansberg (2002) who study the internal structure of a city under different agglomeration forces.

[22]Throughout the paper we assume that each site of our spatial domain provides "enough space" to accommodate the industrial activity implied either by a REE equilibrium or the regulator's optimum. If a constraint of the form $q(r) \leq \bar{q}$, for all $r \in S$, is imposed, then at places where the constraint is binding, peaks will disappear, and it is expected that the overall spatial distribution will be "flatter", as some industrial activity will move from sites where there is no space to accommodate it, to adjacent sites.

where the natural advantage site is *not* an agglomeration point. The explanation is the following: at the optimum with environmental considerations, the regulator realizes the positive interaction of firms located at nearby areas, but he also takes into account the fact that if all firms locate around "one" spatial point, then the cost of environmental policy will be very high. So the optimal solution is to cluster around "two points" and form a bicentric city. We should also notice that the higher transportation cost (beta=0.075) leads, as expected, to a lower concentration of economic activity around the two peaks.[23] When there is no environmental policy, but knowledge spillovers are internalized by the regulator (figures 2g and 2h), a unique cluster emerges around the natural advantage site. The comparison between figures 2e-2f and 2g-2h makes clear that it is the optimal environmental policy that induces a bicentric city. Comparing the REE and the optimum, when there are no environmental considerations, we notice that in the optimum, the internalization of the production externality leads to a higher concentration of economic activity at each spatial point.[24]

Summarizing, our results show that the optimal environmental policy impedes the clustering of economic activity around one spatial point, which would occur in its absence. But, what is probably more important is that at the optimum, there is no concentration around the natural advantage site when knowledge spillovers and environmental policy interact. In other words, while both the absence of environmental policy and a spatially myopic policy lead to the predicted result, according to which a lot of industries locate around the site with the natural advantage, the implementation of the optimal environmental policy breaks down this pattern. This is because when the full cost of emissions is internalized across space, then clustering around the site with the natural advantage generates high social costs which make the cost advantage of this site disappear. The balancing between the centripetal forces (knowledge spillovers and transportation costs) and the centrifugal force (optimal environmental policy) creates cost advantages at two

[23]At the optimum (figures 2e and 2f), the solid line corresponds to $\delta = 3$. The two peaks of that line do not appear in the figure, because we wanted to draw all three curves in one figure, so as to point out the differences. So at the spatial points $r = \frac{\pi}{2}, \frac{3\pi}{2},$ where we have the two peaks, the corresponding distribution value for $\beta = 0.045$ is 1.5×10^7 , and for $\beta = 0.075$ is 1×10^7.

[24]This conclusion is in line with Rossi-Hansberg's (2004) results about the differences between optimal and equilibrium distributions.

other sites. Thus, a bicentric city emerges, since economic activity is attracted by the new cost advantage sites. It should be noted that we cannot have a single "new cost advantage site" because then, as in the case of the port, the intense accumulation of production around this point would make environmental cost increase and the cost advantage disappear.

5.2 *Transportation Cost*

To study how changes in the transportation cost affect the spatial structure of our city, we use the values $\beta = (0.045, 0.06, 0.075)$ for weak ($\delta = 1$) and strong ($\delta = 3$) knowledge spillovers. The high value of β (0.075) was selected to double the per unit price of machinery at the boundaries ($r = 0,\ S$) and the low value of β (0.045) to increase the per unit price of machinery by 50% at the same points. Environmental policy when applied is spatially myopic and stringent $(\psi = 1.5)$.

The results are presented in figure 3. In figure 3a we observe the clustering of economic activity around the city centre at the REE which is the result of the low value of δ. Higher transportation costs (solid line) imply lower densities at the boundaries and at all other points, except for $\bar{r} = \pi$. For $\delta = 3$, low transportation costs (dashed line in figure 3b) induce three peaks, but the main cluster remains at the natural advantage site. However, higher values of β lead to a lower concentration around the two boundary peaks, as it is more expensive now to transport a lot of machinery to spatial points far from the city centre.

When environmental policy is optimal (figures 3e and 3f) we observe again the formation of the two clusters and a bicentric city. The intuition behind this result is similar to the one presented in the previous section. Higher values of β imply lower densities of output around the two peaks. Absence of environmental policy at the REE (figures 3c and 3d) or lack of environmental considerations at the regulator's optimum (figures 3g and 3h) induce a monocentric city. In general, as expected, increases in β decrease economic activity across space.

5.3 *Changes in the Location of the Natural Advantage Site*

The results of the numerical experiments presented above suggest that in the REE, the first nature advantage site will always act as an attractor of economic activity and will lead to the formation of either a monocentric or a polycentric city with the main cluster around that natural advantage site. However, this is not the case for the optimum where the agglomeration forces studied here induce the formation of a bicentric city where neither of the two peaks is located at the spatial point with the inherent advantage.

In this subsection, we show that the above results hold even in the case where we place the natural cost advantage location in different sites of our spatial domain. Figure 4 presents the REE (figures 4a, 4b) and the optimal distribution of economic activity (figures 4c, 4d) when the port is available at two different sites ($\bar{r} = \frac{\pi}{4}$ or $\bar{r} = \frac{3\pi}{4}$). At the REE, the higher concentration of economic activity is again observed around the site with the natural advantage. At the optimum, however, the bicentric city still emerges, but now the two peaks are not symmetric. There is a higher concentration of economic activity in sites which are closer to the first nature advantage site. It should be noted that the two peaks remain at the points $\frac{\pi}{2}$ and $\frac{3\pi}{2}$ from the origin, which means that the location of the peaks is not affected by the location of the port. What is affected, however, is the size of the peaks, as the cluster which is closer to the port is larger. Figures 4c and 4d show that when the port is available at $\bar{r} = \frac{\pi}{4}$ or $\bar{r} = \frac{3\pi}{4}$, the left peak is higher compared to the right one, as expected, since the transportation cost from the port to the spatial point $\frac{3\pi}{2}$ (where the second peak is observed) is higher relative to the transportation cost to the first peak at $\frac{\pi}{2}$.

5.4 *Environmental Policy*

In analyzing the impact from changes in environmental policy, we do not consider optimal emission taxes as defined in Section 4, but only spatially myopic emission taxes at the REE as defined by (5).[25] As already stated, this tax depends on the concentration of pollution at each spatial point and the tax rate is a function of the marginal damage

[25] The imposition of optimal taxes would reproduce the optimum (figures 2 and 3).

caused in the economy by the aggregate level of pollution at a given point. Depending on the stringency of environmental policy, this form of taxation could fully or partly internalize the marginal damage. The strict or the lax environmental policy determines the amount of money firms are obliged to pay for the emissions they generate. The ψ parameter shows the degree of internalization and the stringency of environmental policy. $\psi = 1.5$ means full internalization and every value of ψ which is $0 < \psi < 1.5$ implies lower taxation and a weaker centrifugal force as ψ declines towards zero.

In Figure 5, we present the spatial distribution of economic activity using different values of ψ. Figure 5a is drawn for $\zeta = 0.5$ and 5b for $\zeta = 2$. The higher value of ζ means that pollution is more localized and affects only nearby areas compared to the lower one. Let's explain first why $\zeta = 0.5$ leads to the clustering of economic activity in three peaks, while $\zeta = 2$ forms a unique peak. Under low values of ζ, emissions at each site pollute other sites that are far away. But, if each site is affected by emissions generated at a lot of sites, farther or nearer, the concentration of pollution will be higher at each spatial point. In that case, firms avoid locating all at the same spatial point, so as not to increase further the "price" of emissions. For this reason, we have the clustering of production in three peaks. When pollution is more localized ($\zeta = 2$) emissions generated at one site do not affect other sites a lot and so the "price" of emissions is lower. Then, firms have a stronger incentive to locate near each other in order to benefit from knowledge spillovers. This is the case presented in figure 5b. It should be noted that both in the case of a single cluster and of three clusters, the main cluster emerges at the site with the natural advantage.

As far as the stringency of environmental policy is concerned, the results could be easily predicted. Strict environmental policy and full internalization of marginal damage (dotted lines in figure 5) lead to a lower distribution of production in every case. On the other hand, more lenient environmental regulations (solid lines in figure 5) not only lead to higher production at each site but also promote the agglomeration of economic activity around the city centre. So the intuition is simple: environmental policy deters the clustering of production and makes the distribution of economic activity flatter.[26] In other words, strict environmental policy makes the distribution of economic activity less uneven. This result is consistent with the empirical literature, according to which environmental regulations restrict economic activity and result in a spreading out or an exiting of polluting firms.[27]

6 Conclusions

We develop a model of a single city - of length S - in which firms are free to choose where to locate. The city has a nonuniform internal structure because of externalities in production, the existence of a location with natural cost advantage and the assumption of pollution diffusing in space which implies the implementation of environmental policy. The first two forces have been identified in the theoretical and empirical literature as two of the most important forces that work to encourage the concentration of economic activity around the natural advantage site. Thus, our intention was to study whether the consideration of environmental issues can change the very well-known "monocentric city" result.

Our results suggest that under an optimal (non-spatially myopic) environmental policy, the monocentric city collapses to a bicentric city. The two clusters formed in that case result from the full internalization of environmental damages and knowledge spillovers. On the other hand, the REE under a spatially myopic environmental policy results either in a monocentric or in a polycentric city. What is also significant is that in both REE cases, the port attracts a large number of firms and the major cluster of economic activity emerges at this site. However, and in contrast to the equilibrium case, in the optimum, neither of the two clusters occurs at the natural advantage site which repels agglomeration because, as explained in the text, it loses its cost advantage when environmental damages are taken into account.

Notice that the above results hold even if we choose a spatial point different from

[26]The proof of flatness is presented in Appendix D.

[27]See Introduction: Greenstone (2002), Henderson (1996).

the city centre for the location of the natural advantage site. Then, at the REE, firms "follow" the port and as a result, there is still a high concentration of economic activity around this spatial point. Furthermore, the optimal environmental policy induces again a bicentric city, but now the two peaks are not symmetric: the peak which is closer to the port is always higher. Finally, when we assume that no environmental policy is enforced for the emissions generated in the production process, then the spatial patterns derived are the same in both cases of the REE and the optimum: a monocentric city emerges and economic activity is concentrated around a unique site, which is always the spatial point with the natural advantage.

A potential policy implication of our results suggests that when a natural advantage site is associated with spatial knowledge spillovers, and with emissions of pollutants which diffuse in space and need to be regulated, then the optimal spatial design seems to be a bicentric structure with two clusters which do not coincide with the natural advantage site. In general, sites with inherent advantages can lose their comparative advantage when social costs at these spatial points become higher and higher. Then, other sites appear to be more attractive as they provide stronger cost advantages compared to the natural ones.

Acknowledgments

The authors would like to thank participants at the 2009 Conference of the European Association of Environmental and Resource Economists (EAERE) in Amsterdam, as well as the seminar participants at the Stockholm School of Economics and Athens University of Economics and Business for valuable comments. A very early version of this paper was presented at the 2008 EAERE Summer School on Space in Unified Models of Economy and Ecology in Venice. The authors thank the participants at this event for helpful discussions.

References

Arnott, R., Hochman, O., Rausser, G.C., 2008. Pollution and land use: optimum and decentralization. J. Urban Econ. 64, 390-407.

Bottazzi, L., Peri, G., 2003. Innovation and spillovers in regions: evidence from European patent data. Europ. Econ. Rev. 47, 687-710.

Brock, W., 1977. A polluted golden age, in: Smith, V. (Eds.), Economics of Natural and Environmental Resources. Gordon and Breach, New York, pp. 441-462.

Carlino, G.A., Chatterjee, S., Hunt, R.M., 2007. Urban density and the rate of invention. J. Urban Econ. 61, 389-419.

Ellison, G., Glaeser, E.L., 1999. The geographic concentration of industry: does natural advantage explain agglomeration? Amer. Econ. Rev. Papers and Proceedings 89, 311-316.

Fujita, M., Krugman, P., Venables, A.J., 1999. The Spatial Economy: Cities, Regions and International Trade, first ed. MIT Press, Cambridge, MA.

Fujita, M., Thisse, J.-F., 2002. Economics of Agglomeration: Cities, Industrial Location and Regional Growth, first ed. Cambridge University Press, Cambridge.

Greenstone, M., 2002. The impacts of environmental regulations on industrial activity: evidence from the 1970 and the 1977 Clean Air Act amendments and the Census of Manufactures. J. Polit. Econ. 110, 1175-1219.

Henderson, J.V., 1996. Effects of air quality regulation. Amer. Econ. Rev. 86, 789-813.

Jouvet, P.-A., Michel, P., Rotillon, G., 2005. Optimal growth with pollution: how to use pollution permits? J. Econom. Dynam. Control 29, 1597-1609.

Keller, W., 2002. Geographic localization of international technology diffusion. Amer. Econ. Rev. 92, 120-142.

Krugman, P., 1999. The role of geography in development. Int. Reg. Sci. Rev. 22, 142-161.

LaFountain, C., 2005. Where do firms locate? Testing competing models of agglomeration. J. Urban Econ. 58, 338-366.

Lange, A., Quaas, M., 2007. Economic geography and the effect of environmental pollution on agglomeration. BE J. Econ. Anal. Poli. 7, Article 52.

Lucas Jr., R.E, 2001. Externalities and cities. Rev. Econ. Dynam. 4, 245-274.

Lucas Jr., R.E., Rossi-Hansberg, E., 2002. On the internal structure of cities. Econometrica 70, 1445-1476.

Maleknejad, K., Aghazadeh, N., Rabbani, M., 2006. Numerical solution of second kind Fredholm integral equations system by using a Taylor-series expansion method. Appl. Math. Comput. 175, 1229-1234.

Marshall, A., 1920. Principles of Economics, eighth ed. Macmillan and Co., London.

Moiseiwitsch, B.L., 2005. Integral Equations, first ed. Dover Publications, New York.

Polyanin, A.D., Manzhirov, A.V., 1998. Handbook of Integral Equations, first ed. Chapman & Hall/CRC Press, Boca Raton.

Rauscher, M., 1994. On ecological dumping. Oxford Econ. Pap. 46, 822-840.

Roos, M.W.M., 2005. How important is geography for agglomeration? J. Econ. Geogr. 5, 605-620.

Rosenthal, S.S., Strange, W.C., 2001. The determinants of agglomeration. J. Urban Econ. 50, 191-229.

Rosenthal, S.S., Strange, W.C., 2004. Evidence on the nature and sources of agglomeration economies, in: Henderson, J.V., Thisse, J.-F., (Eds.), Handbook of Regional and Urban Economics. Elsevier Publ., Amsterdam, pp. 2119-2171.

Rossi-Hansberg, E., 2004. Optimal urban land use and zoning. Rev. Econ. Dynam. 7, 69-106.

Rossi-Hansberg, E., 2005. A spatial theory of trade. Amer. Econ. Rev. 95, 1464-1491.

Stokey, N.L., 1998. Are there limits to growth? Int. Econ. Rev. 39, 1-31.

Tahvonen, O., Kuuluvainen, J., 1993. Economic growth, pollution and renewable resources. J. Environ. Econ. Manage. 24, 101-118.

Van Marrewijk, C., 2005. Geographical economics and the role of pollution on location. ICFAI J. Environ. Econ. 3, 28-48.

Xepapadeas, A., 2005. Economic growth and the environment, in: Mäler, K.-G., Vincent, J., (Eds.), Handbook of Environmental Economics, vol 3. Elsevier Publ., pp. 1219-1271.

Appendix A: *Solving a system of second kind Fredholm integral equations, following the modified Taylor-series expansion method* (Maleknejad et al., 2006).

Solving for the Rational Expectations Equilibrium: we take logs of (10a)-(10c). Then the FONC become:

$$\ln p + \ln a + \gamma\delta \int_0^S e^{-\delta(r-s)^2} \ln (L(s))ds + (a-1)\ln L(r) + b \ln K(r) + c \ln E(r) = \ln w$$

$$\ln p + \ln b + \gamma\delta \int_0^S e^{-\delta(r-s)^2} \ln (L(s))ds + a\ln L(r) + (b-1) \ln K(r) + c \ln E(r)$$
$$= \ln p_K + \beta(r-\overline{r})^2$$

$$\ln p + \ln c + \gamma\delta \int_0^S e^{-\delta(r-s)^2} \ln (L(s))ds + a\ln L(r) + b \ln K(r) + (c-1) \ln E(r)$$
$$= \ln \psi + (\phi - 1) \int_0^S e^{-\zeta(r-s)^2} \ln (E(s))\, ds$$

Setting $\ln L = y$, $\ln K = x$ and $\ln E = \varepsilon$, we obtain the following system:

$$\gamma\delta \int_0^S e^{-\delta(r-s)^2} y(s)ds + (a-1)y(r) + bx(r) + c\varepsilon(r) = \ln w - \ln p - \ln a$$

$$\gamma\delta \int_0^S e^{-\delta(r-s)^2} y(s)ds + ay(r) + (b-1)x(r) + c\varepsilon(r) = \ln p_K + \beta(r-\overline{r})^2 - \ln p - \ln b$$

$$\gamma\delta \int_0^S e^{-\delta(r-s)^2} y(s)ds + ay(r) + bx(r) + (c-1)\varepsilon(r) + (1-\phi) \int_0^S e^{-\zeta(r-s)^2} \varepsilon(s)\, ds$$
$$= \ln \psi - \ln p - \ln c$$

We transform the system in order to obtain a system of second kind Fredholm integral equations with symmetric kernels:

$$\underbrace{\begin{pmatrix} \gamma\delta & 0 \\ \gamma\delta & 0 \\ \gamma\delta & (1-\phi) \end{pmatrix} \begin{pmatrix} \int_0^S e^{-\delta(r-s)^2} y(s)ds \\ \int_0^S e^{-\zeta(r-s)^2} \varepsilon(s)ds \end{pmatrix} + \begin{pmatrix} \ln a + \ln p - \ln w \\ \ln p + \ln b - \ln p_K - \beta(r-\overline{r})^2 \\ \ln c + \ln p - \ln \psi \end{pmatrix}}_{\text{B}}$$

$$= \underbrace{\begin{pmatrix} 1-a & -b & -c \\ -a & 1-b & -c \\ -a & -b & 1-c \end{pmatrix}}_{\text{A}} \underbrace{\begin{pmatrix} y(r) \\ x(r) \\ \varepsilon(r) \end{pmatrix}}_{\text{Z}}$$

$$B = AZ \Rightarrow A^{-1}B = Z \quad \text{where} \quad A^{-1} = \begin{pmatrix} \frac{1-b-c}{1-a-b-c} & \frac{b}{1-a-b-c} & \frac{c}{1-a-b-c} \\ \frac{a}{1-a-b-c} & \frac{1-a-c}{1-a-b-c} & \frac{c}{1-a-b-c} \\ \frac{a}{1-a-b-c} & \frac{b}{1-a-b-c} & \frac{1-a-b}{1-a-b-c} \end{pmatrix}$$

From $A^{-1}B = Z$, we derive the following system of second kind Fredholm integral equations:

$$\begin{aligned} \tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2}y(s)ds + \tfrac{c(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}\varepsilon(s)ds + g_1(r) &= y(r) \quad \text{(A1)} \\ \tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2}y(s)ds + \tfrac{c(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}\varepsilon(s)ds + g_2(r) &= x(r) \quad \text{(A2)} \\ \tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2}y(s)ds + \tfrac{(1-a-b)(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}\varepsilon(s)ds + g_3(r) &= \varepsilon(r) \quad \text{(A3)} \end{aligned}$$

where:

$$\begin{aligned} g_1(r) &= \tfrac{1}{1-a-b-c}\{(1-b-c)\ [\ln a + \ln p - \ln w] + \\ &\quad b\ [\ln p + \ln b - \ln p_K - \beta(r-\bar{r})^2] + c\ [\ln c + \ln p - \ln\psi]\} \\ g_2(r) &= \tfrac{1}{1-a-b-c}\{a\ [\ln a + \ln p - \ln w] + \\ &\quad (1-a-c)\ [\ln p + \ln b - \ln p_K - \beta(r-\bar{r})^2] + c\ [\ln c + \ln p - \ln\psi]\} \\ g_3(r) &= \tfrac{1}{1-a-b-c}\{a\ [\ln a + \ln p - \ln w] + \\ &\quad b\ [\ln p + \ln b - \ln p_K - \beta(r-\bar{r})^2] + (1-a-b)\ [\ln c + \ln p - \ln\psi]\} \end{aligned}$$

Taylor-series expansions can be made for the solutions $y(s)$ and $\varepsilon(s)$:

$$\begin{aligned} y(s) &= y(r) + y'(r)(s-r) + \frac{1}{2}y''(r)(s-r)^2 \\ \varepsilon(s) &= \varepsilon(r) + \varepsilon'(r)(s-r) + \frac{1}{2}\varepsilon''(r)(s-r)^2 \end{aligned}$$

Substituting the expansions into the integrals of the system (A1)-(A3), we get:

$$\begin{aligned} y(r) &= \tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2}\ \{y(r)+y'(r)(s-r)+\frac{1}{2}y''(r)(s-r)^2\}\ ds + \\ &\quad \tfrac{c(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}\{\varepsilon(r)+\varepsilon'(r)(s-r)+\frac{1}{2}\varepsilon''(r)(s-r)^2\}\ ds + g_1(r) \end{aligned} \tag{A4}$$

$$\begin{aligned} x(r) &= \tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2}\ \{y(r)+y'(r)(s-r)+\frac{1}{2}y''(r)(s-r)^2\}\ ds + \\ &\quad \tfrac{c(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}\{\varepsilon(r)+\varepsilon'(r)(s-r)+\frac{1}{2}\varepsilon''(r)(s-r)^2\}\ ds + g_2(r) \end{aligned} \tag{A5}$$

$$\begin{aligned} \varepsilon(r) &= \tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2}\ \{y(r)+y'(r)(s-r)+\frac{1}{2}y''(r)(s-r)^2\}\ ds + \\ &\quad \tfrac{(1-a-b)(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}\{\varepsilon(r)+\varepsilon'(r)(s-r)+\frac{1}{2}\varepsilon''(r)(s-r)^2\}\ ds + g_3(r) \end{aligned} \tag{A6}$$

Rewriting the equations we have:

$$\begin{aligned} g_1(r) &= \left[1-\tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2} ds\right] y(r) - \left[\tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2}(s-r)ds\right] y'(r) \\ &\quad -\left[\frac{1}{2}\ \tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2}(s-r)^2 ds\right] y''(r) - \left[\tfrac{c(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2} ds\right]\varepsilon(r) - \\ &\quad \left[\tfrac{c(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}(s-r)ds\right]\varepsilon'(r) - \left[\frac{1}{2}\ \tfrac{c(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}(s-r)^2 ds\right]\varepsilon''(r) \end{aligned} \tag{A7}$$

$$\begin{aligned} g_2(r) &= x(r) - \left[\tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2} ds\right] y(r) - \left[\tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2}(s-r)ds\right] y'(r) \\ &\quad -\left[\frac{1}{2}\ \tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2}(s-r)^2 ds\right] y''(r) - \left[\tfrac{c(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2} ds\right]\varepsilon(r) - \\ &\quad \left[\tfrac{c(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}(s-r)ds\right]\varepsilon'(r) - \left[\frac{1}{2}\ \tfrac{c(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}(s-r)^2 ds\right]\varepsilon''(r) \end{aligned} \tag{A8}$$

$$g_3(r) = -\left[\tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2}ds\right]y(r) - \left[\tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2}(s-r)ds\right]y'(r) \qquad \text{(A9)}$$
$$-\left[\frac{1}{2}\ \tfrac{\gamma\delta}{1-a-b-c}\int_0^S e^{-\delta(r-s)^2}(s-r)^2ds\right]y''(r) + \left[1 - \tfrac{(1-a-b)(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}ds\right]\varepsilon(r) -$$
$$\left[\tfrac{(1-a-b)(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}(s-r)ds\right]\varepsilon'(r) - \left[\frac{1}{2}\ \tfrac{(1-a-b)(1-\phi)}{1-a-b-c}\int_0^S e^{-\zeta(r-s)^2}(s-r)^2ds\right]\varepsilon''(r)$$

If the integrals in equations (A7)-(A9) can be solved analytically, then the bracketed quantities are functions of r alone. So (A7)-(A9) become a linear system of ordinary differential equations that can be solved, if we use an appropriate number of boundary conditions.

To construct boundary conditions we differentiate (A1) and (A3):

$$\begin{aligned} y'(r) &= \tfrac{\gamma\delta}{1-a-b-c}\int_0^S -2\delta\ (r-s)\ e^{-\delta(r-s)^2}\ y(s)\ ds + \\ &\quad \tfrac{c(1-\phi)}{1-a-b-c}\int_0^S -2\zeta\ (r-s)\ e^{-\zeta(r-s)^2}\ \varepsilon(s)\ ds + g_1'(r) \end{aligned} \qquad \text{(A10)}$$

$$\begin{aligned} y''(r) &= \tfrac{\gamma\delta}{1-a-b-c}\int_0^S \left[-2\delta + 4\delta^2\ (r-s)^2\right]\ e^{-\delta(r-s)^2}\ y(s)\ ds + \\ &\quad \tfrac{c(1-\phi)}{1-a-b-c}\int_0^S \left[-2\zeta + 4\zeta^2\ (r-s)^2\right]\ e^{-\zeta(r-s)^2}\ \varepsilon(s)\ ds + g_1''(r) \end{aligned} \qquad \text{(A11)}$$

$$\begin{aligned} \varepsilon'(r) &= \tfrac{\gamma\delta}{1-a-b-c}\int_0^S -2\delta\ (r-s)\ e^{-\delta(r-s)^2}\ y(s)\ ds + \\ &\quad \tfrac{(1-a-b)(1-\phi)}{1-a-b-c}\int_0^S -2\zeta\ (r-s)\ e^{-\zeta(r-s)^2}\ \varepsilon(s)\ ds + g_3'(r) \end{aligned} \qquad \text{(A12)}$$

$$\begin{aligned} \varepsilon''(r) &= \tfrac{\gamma\delta}{1-a-b-c}\int_0^S \left[-2\delta + 4\delta^2\ (r-s)^2\right]\ e^{-\delta(r-s)^2}\ y(s)\ ds + \\ &\quad \tfrac{(1-a-b)(1-\phi)}{1-a-b-c}\int_0^S \left[-2\zeta + 4\zeta^2\ (r-s)^2\right]\ e^{-\zeta(r-s)^2}\ \varepsilon(s)\ ds + g_3''(r) \end{aligned} \qquad \text{(A13)}$$

We substitute $y(r)$ and $\varepsilon(r)$ for $y(s)$ and $\varepsilon(s)$ in equations (A10) - (A13):

$$y'(r) = \left[\frac{\gamma\delta}{1-a-b-c}\int_0^S -2\delta\ (r-s)\ e^{-\delta(r-s)^2}\ ds\right] y(r) + \left[\frac{c(1-\phi)}{1-a-b-c}\int_0^S -2\zeta\ (r-s)\ e^{-\zeta(r-s)^2}\ ds\right]\varepsilon(r) + g_1'(r) \quad \text{(A14)}$$

$$y''(r) = \left[\frac{\gamma\delta}{1-a-b-c}\int_0^S \left[-2\delta + 4\delta^2\ (r-s)^2\right]\ e^{-\delta(r-s)^2}\ ds\right] y(r) + \left[\frac{c(1-\phi)}{1-a-b-c}\int_0^S \left[-2\zeta + 4\zeta^2\ (r-s)^2\right]\ e^{-\zeta(r-s)^2}\ ds\right]\varepsilon(r) + g_1''(r) \quad \text{(A15)}$$

$$\varepsilon'(r) = \left[\frac{\gamma\delta}{1-a-b-c}\int_0^S -2\delta\ (r-s)\ e^{-\delta(r-s)^2}\ ds\right] y(r) + \left[\frac{(1-a-b)(1-\phi)}{1-a-b-c}\int_0^S -2\zeta\ (r-s)\ e^{-\zeta(r-s)^2}\ ds\right]\varepsilon(r) + g_3'(r) \quad \text{(A16)}$$

$$\varepsilon''(r) = \left[\frac{\gamma\delta}{1-a-b-c}\int_0^S \left[-2\delta + 4\delta^2\ (r-s)^2\right]\ e^{-\delta(r-s)^2}\ ds\right] y(r) + \left[\frac{(1-a-b)(1-\phi)}{1-a-b-c}\int_0^S \left[-2\zeta + 4\zeta^2\ (r-s)^2\right]\ e^{-\zeta(r-s)^2}\ ds\right]\varepsilon(r) + g_3''(r) \quad \text{(A17)}$$

In equations (A14)-(A17), we observe that $y'(r)$, $y''(r)$, $\varepsilon'(r)$, $\varepsilon''(r)$ are functions of $y(r)$, $\varepsilon(r)$, $g_1'(r)$, $g_1''(r)$, $g_3'(r)$, $g_3''(r)$. Substituting them into (A7), (A8) & (A9), we have a linear system of three algebraic equations that can be solved using Mathematica.

Appendix B: The same method of modified Taylor-series expansion was used in order to solve for the regulator's optimum. The FONC for the optimum, (16a), (16c), contain two terms that need to be determined: $\frac{\vartheta z(r)}{\vartheta L(r)} = \delta\frac{1}{L(r)}\int_0^S e^{-\delta(r-s)^2}ds$ and

$\frac{\vartheta X(r)}{\vartheta E(r)} = \frac{1}{E(r)}\ e^{\int_0^S \left[e^{-\zeta(r-s)^2}\ln E(s)\right]ds}\int_0^S e^{-\zeta(s-r)^2}ds$. Using these two terms, we follow the method analysed in Appendix A to find the optimal solution.

Appendix C: *Transformation of the system (11) to a single Fredholm equation of second kind* (Polyanin and Manzhirov, 1998).

We define the functions $Y(r)$ and $G(r)$ on $[0, 3S]$, where $Y(r) = y_i(r-(i-1)S)$ and $G(r) = g_i(r-(i-1)S)$ for $(i-1)S \leq r \leq iS$.[28] Next, we define the kernel $C(r,s)$ on the square $[0,3S]\times[0,3S]$ as follows: $C(r,s) = k_{ij}(r-(i-1)S,\ s-(j-1)S)$ for $(i-1)S \leq r \leq iS$ and $(j-1)S \leq s \leq jS$.

So the system (11) can be rewritten as the single Fredholm equation:

$Y(r) - \frac{1}{1-a-b-c}\int_0^{3S} C(r,s)\ Y(s)\ ds = G(r),$ where $0 \leq r \leq 3S$.

If the kernels $k_{ij}(r,s)$ are square integrable on the square $[0,S]\times[0,S]$ and $g_i(r)$ are square integrable functions on $[0,S]$, then the kernel $C(r,s)$ is square integrable on the new square: $[0,3S]\times[0,3S]$ and $G(r)$ is square integrable on $[0,3S]$.

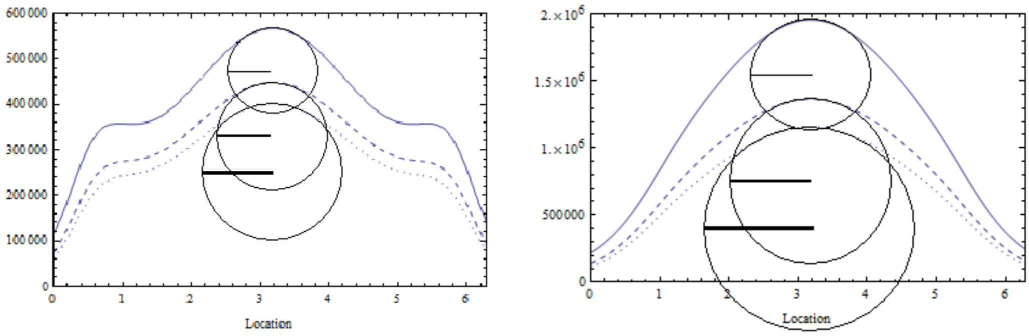
Appendix D: Figure 5: *Proof of flatness.*

In order to measure flatness, we use the concept of curvature. Curvature is the amount by which a geometric object deviates from being flat, or straight in the case of a line. To measure curvature of a line we can use the approximation: $\kappa \approx \left|\frac{d^2q}{dr^2}\right|$, where $q(r) = \exp(\gamma z(r))L(r)^a K(r)^b E(r)^c$ is the production function. We use Mathematica to measure the curvature of lines in figure 5. In figure 5a, at the point $r=\pi$, the dotted line has $\kappa(\pi) = 168,174,$ the dashed line has $\kappa(\pi) = 190,340$ and the solid line has $\kappa(\pi) = 248,240$. In figure 5b, at the point $r=\pi$, the dotted line has $\kappa(\pi) = 360,077$, the dashed line has $\kappa(\pi) = 425,289$ and the solid line has $\kappa(\pi) = 608,352$. The flattest curve is the one with the lowest curvature value, i.e. the dotted line (in both cases).

Another way to measure the curvature at a specific point is to use the approach of the osculating circle. According to this approach, from any point of any curve, where the curvature is non-zero, there is a unique circle which most closely approximates the curve near that point. This is the osculating circle at that point. The radius (R) of the osculating circle determines the curvature at that point in the following way: $\kappa = \frac{1}{R}$.

So we draw the osculating circles at point $r=\pi$, of the curves in figure 5:

[28] We assume that $y_1 = y$, $y_2 = x$ and $y_3 = \varepsilon$, so as to follow the notation of our model.



(a) (b)

Figure 5(a): Let R_{11} be the radius of the osculating circle of the solid line, R_{12} be the radius of the osculating circle of the dashed line and R_{13} be the radius of the osculating circle of the dotted line, then it is obvious that $R_{11} < R_{12} < R_{13}$. Also, if the corresponding curvatures are $\kappa_{11} = \frac{1}{R_{11}}$, $\kappa_{12} = \frac{1}{R_{12}}$ and $\kappa_{13} = \frac{1}{R_{13}}$, then $\kappa_{11} > \kappa_{12} > \kappa_{13.}$ As a result, the dotted line is the flattest curve. In a similar way, we prove that the dotted curve of figure 5(b) is the flattest one.

Figures

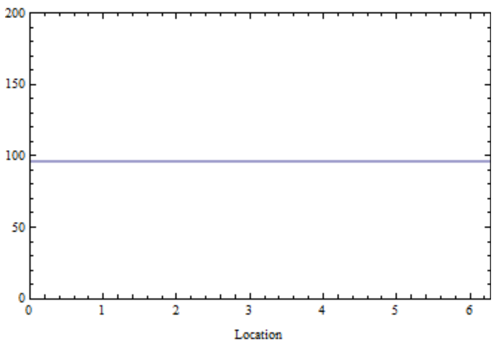
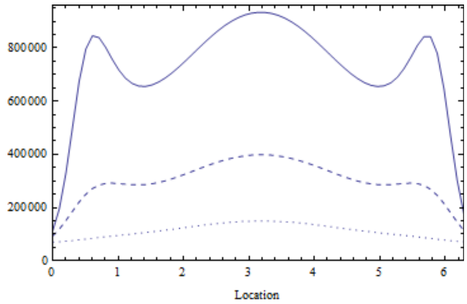
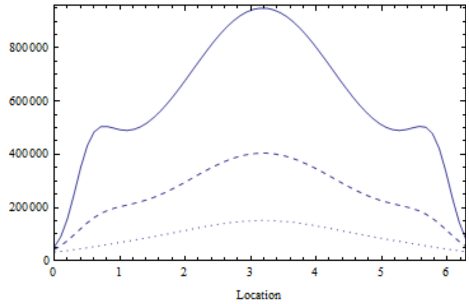


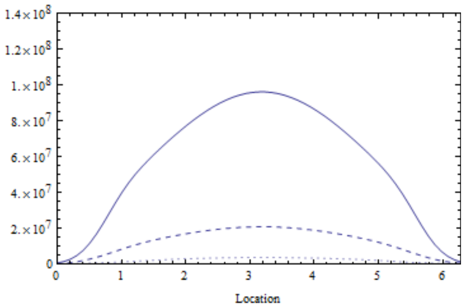
Figure 1: Benchmark case: The Distribution of Economic Activity under no Agglomeration Forces



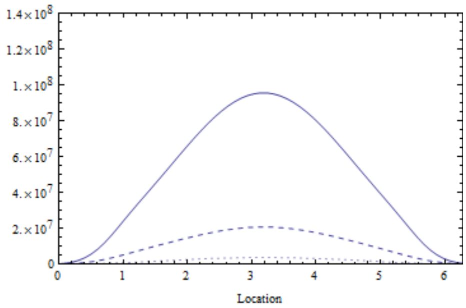
(a) REE (beta=0.045)



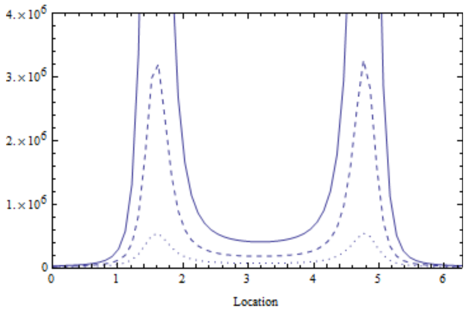
(b) REE (beta=0.075)



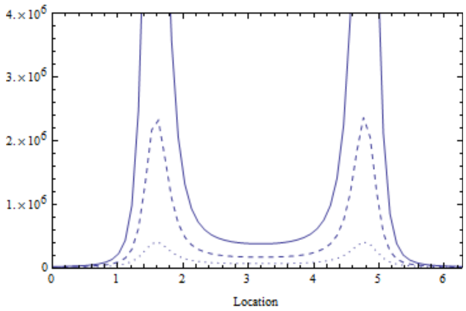
(c) REE without Environmental Considerations (beta=0.045)



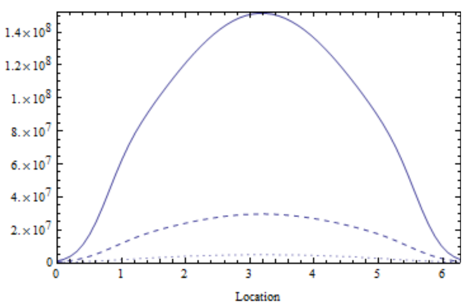
(d) REE without Environmental Considerations (beta=0.075)



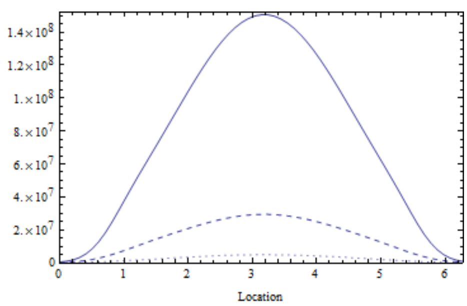
(e) Optimum (beta=0.045)



(f) Optimum (beta=0.075)

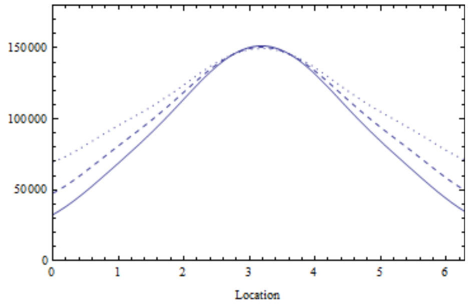


(g) Optimum without Environmental Considerations (beta=0.045)

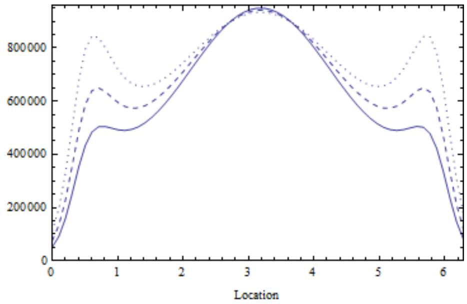


(h) Optimum without Environmental Considerations (beta=0.075)

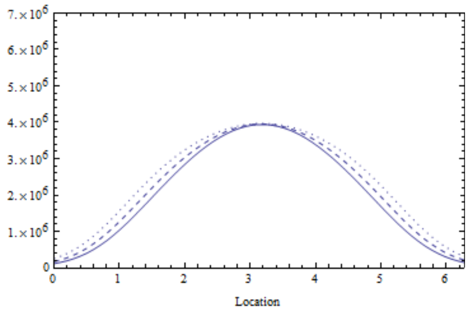
Figure 2: The Distribution of Economic Activity: Changes in the values of delta. Dotted Line: delta=1, Dashed Line: delta=2, Solid Line: delta=3



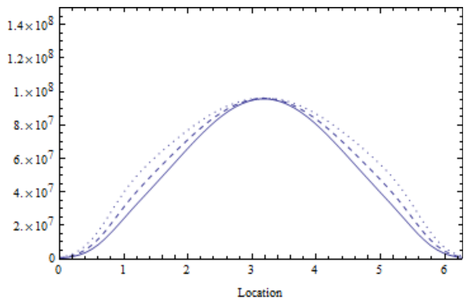
(a) REE (delta=1)



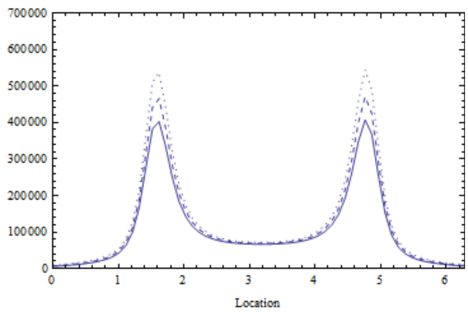
(b) REE (delta=3)



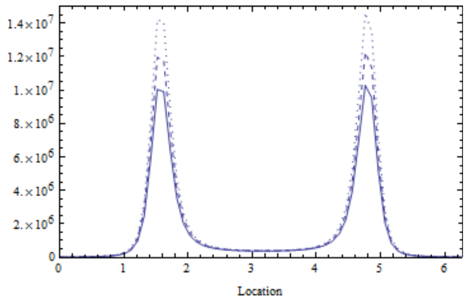
(c) REE without Environmental Considerations (delta=1)



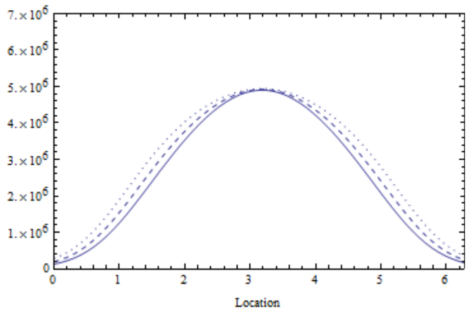
(d) REE without Environmental Considerations (delta=3)



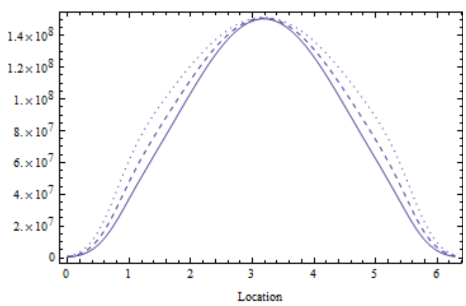
(e) Optimum (delta=1)



(f) Optimum (delta=3)

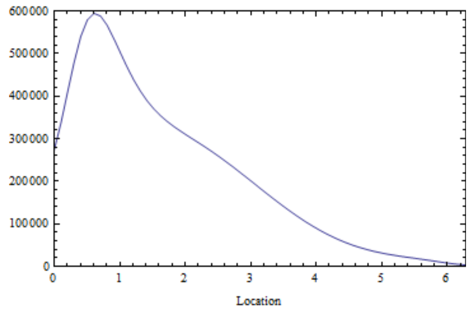


(g) Optimum without Environmental Considerations (delta=1)

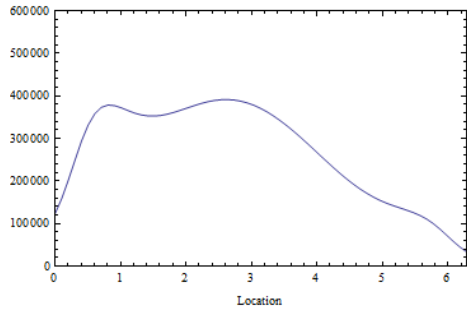


(h) Optimum without Environmental Cosiderations (delta=3)

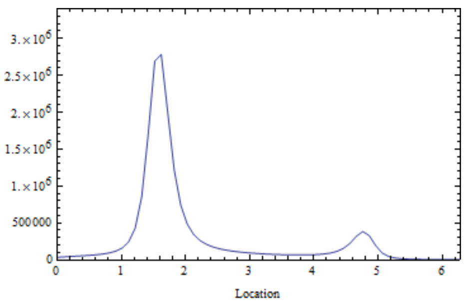
Figure 3: The Distribution of Economic Activity: Changes in the values of transportation cost. Dotted Line: beta=0.045, Dashed Line: beta=0.06, Solid Line: beta=0.075



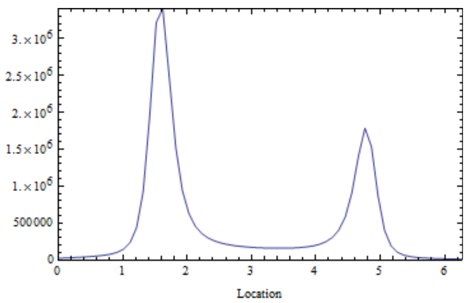
(a) REE ($\bar{r} = \frac{\pi}{4}$)



(b) REE ($\bar{r} = \frac{3\pi}{4}$)

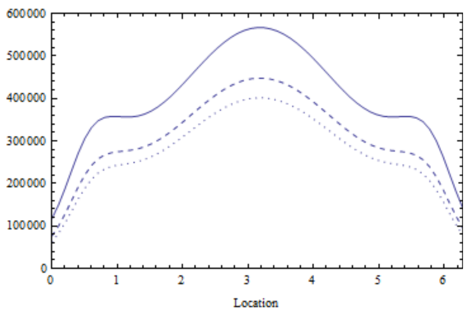


(c) Optimum ($\bar{r} = \frac{\pi}{4}$)

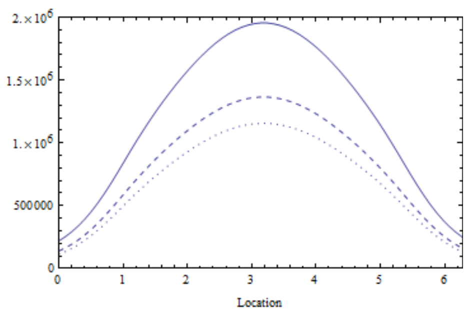


(d) Optimum ($\bar{r} = \frac{3\pi}{4}$)

Figure 4: The Distribution of Economic Activity: Changes in the Location (rbar) of the Port (beta=0.06, delta=2)



(a) $\zeta = 0.5$



(b) $\zeta = 2$

Figure 5: The Distribution of Economic Activity: Changes in the values of psi. Dotted Line: psi=1.5, Dashed Line: psi=0.9, Solid Line: psi=0.3.