Economic Agglomeration and Environmental Policy

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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 iceberg transportation costs act as centripetal forces. We study the agglomeration effects caused by trade-offs between centripetal and centrifugal forces. The above effects govern firms' location decisions and as a result, they define the distribution of economic activity across space.

JEL CODES: R3, Q5, H2.

KEYWORDS: Agglomeration, Spatial Economics, Environmental Policy, Knowledge Spillovers, Transportation Cost.

1. Introduction

The spatial aspect of economic activity hadn't attracted a lot of attention by mainstream economics until recently. However, the distribution of population and activity across the landscape is undoubtedly uneven. Agglomeration - the clustering of economic activity - once created, is sustained as a result of a circular logic. For example, a shop is more probable to locate in a shopping street than in the centre of a residential area with no shops around. The same happens with specialized economic regions, like Silicon Valley. Silicon Valley is so famous for the development of a high-tech economic center and its large number of innovators and manufacturers, that the term is now generally used as a metonym for the high-tech sector.

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Silicon Valley isn't the only example of agglomeration. A lot of metropolitan areas - large population centers - play a major role in economic activity. In Europe, Île-de-France is the most populated region of France. It accounts for 2.2% of the area of the country and 18.1% of its population. It has more residents than Belgium, Greece, Austria, Portugal or Sweden. Economically, Île-de-France is one of the richest regions in the world and produces 33% of GDP of France[3]. Moreover, more than 30% of national GDP in the United Kingdom, Sweden and Japan are accounted for by London (31.6%), Stockholm (31.5%) and Tokyo (30.4%). More importantly, most OECD metropolitan areas have a higher GDP per capita than their national average, a higher labor productivity level and many of them tend to have faster growth rates than their countries.

The concept "metropolitan area" is based on the concept of a business or labor market area and is typically defined as an employment core (an area with a high density of available jobs) and the surrounding areas that have strong commuting ties to the core. Tokyo, Seoul, Mexico City and New York City are some examples of the largest metropolitan areas in the world[4]. They may not be specialized in a certain type of industy, like Silicon Valley, but they undoubtedly count a large number of industries. This process of clustering of economic activity is studied by agglomeration economics.

Despite their particular importance and interest, the spatial decisions of firms and economic agents haven't been studied sufficiently in the past. Why do financial and communication industries locate in New York? Why are restaurants clustered in a certain neighbourhood and why the same thing happens with bookshops, cafés and high-tech shops? Why is Hollywood known for its famous film-makers and for the greatest firm industries in the world? Understanding these trends is crucial for the design of effective policies.

[3] Its total GDP was €500.8 billion in 2006 with a per capita GDP at €43,370 the same year.

[4] For a review of metropolitan areas, see OECD (2006).

Von Thünen (1826) was one of the first who tried to explain the pattern of land use around a city or a central business district, by assuming the existence of that central focus. Alonso (1964) reinterpreted von Thünen's model by substituting the central business district for an isolated town. The main disadvantage of these models is that although they give an explanation of land use surrounding a town, they simply assume the existence of the town. Hotelling's famous paper (1929) focuses on the strategic interactions between firms' location decisions, treating the geographical distribution of demand and resources as exogenous.

Henderson (1974) constructed a model, in which a system of cities evolves from a tension between centripetal and centrifugal forces. The centripetal force arises from assumed localized external economies in production, while the centrifugal force is the urban land rent. Earlier, Mills (1967) had studied the external economies associated with geographic concentration of industry within a city, on one side, and diseconomies such as commuting costs, on the other. This kind of models proves that the relationship between the size of a city and the utility of a representative resident is an inverted U (Fujita et al, 1999).

In 1990's, space started attracting the interest of economists again. According to Krugman (1998), the reason for this renewed interest was the fact that imperfect competition is now possible to model and concepts like unexhausted scale economies are no longer intractable. The result was the emergence of New Economic Geography, which represents a new branch of spatial economics and aims to explain the formation of a large variety of economic agglomeration in geographical space, using a general equilibrium framework (Fujita and Mori, 2005). Economic models of agglomeration take into account the centripetal forces that pull economic activities together and the centrifugal forces that push them apart, studying the trade-offs between various forms of increasing returns and different types of mobility costs (eg. Krugman 1991, 1993, Fugita, Krugman and Mori, 1999).

In most models of New Economic Geography, agglomeration forces arise from linkage effects among consumers and industries, neglecting all other possible sources of agglomeration economies such as knowledge externalities and information spillovers. However, some recent studies have included knowledge externalities in a spatial context (Lucas, 2001, Lucas and Rossi-Hansberg, 2002, Rossi-Hansberg, 2005). These kind of models have three forces that define the equilibrium allocation of business and residential areas: transportation costs, production externalities and immobility of factors.

All the models, we have already refered to, assume that the spatial area under study is homogenious. Contrary to this fact, economic activities are spatially concentrated because of dissimilarities in natural features, such as rivers, harbors or even exhaustible resources that are available in a certain point in space. This "first nature" advantage hasn't been studied a lot yet. An exception is Fujita and Mori's paper (1996) that explained the role of ports in the formation of cities, using an icreasing returns model. This assumption of nonuniformity in geographical space will be introduced in our model too.

Furthermore, cities are important generators of wealth, employment and productivity growth. The growing economic importance of places with high concentration of economic activity, such as metropolitan areas, raises important policy issues. More precisely, these economic activities are not only associated with positive externalities, but also with certain negative externalities, such as congestion, pollution or high crime rates. Considering these issues, we will try to model the problem of pollution and explain the spatial patterns of economic activity[5].

According to Rauscher (2006), pollution promotes dispersion, i.e., a pattern where the economic activity tends to be evenly distributed in space. An example of this dispersion is the fact that governments make nuclear power

[5] Van Marrewijk (2005), Quaas et Lange (2004, 2007) study the effect of pollution on agglomeration using Krugman's core-periphery model (1991) or Forslid and Ottaviano's model (2003).

stations locate in regions with low concentration of economic activity and population. In general, polluting firms are made to migrate to clean areas where they will be subject to less stringent regulation. In an econometric analysis, Mulligan and Schmidt (2005), show that major industry groups became more evenly spread over the entire space-economy during 1958-1995. According to another recent study (Elbers and Withagen, 2004), pollution and evironmental policy tend to countervail clustering that would occur in their absence. To put it differently, environmental policy acts as a centrifugal force.

In this context, we will study the spatial structure of a single city when firms are free to choose where to locate. As far as the production is concerned, we assume positive knowledge spillovers. There is also a resource available in a certain point in the area under study. This resource could be coal or oil and is used in the production function. So, we impose a "first nature" advantage to our city. What we *further* assume here is that the use of the resource generates emissions. So, the government, in order to avoid a high concentration of emissions in a single area, adapts environmental regulations. These regulations impose significant production costs to firms. We assume that the environmental regulations refer to general environmental costs such as taxes or the cost of controlling the environment and imposing zoning systems which all increase with the concentration of pollution. As a result, the use of the resource becomes more expensive and firms have to pay an extra amount of money that depends not only on their own emissions but also on the aggregate concentration of emissions in the point they decide to locate. They higher the number of firms in a certain point, the higher the concentration of emissions in that point. Now, firms have to take into account two things: if they locate near other firms, they will benefit from positive knowledge spillovers, but they will have to pay a higher resource price. Under these assumption, we define the equilibrium concentration of economic activity. We will construct employment and resource-use density maps of a single city and show how changes in paremetres change these maps.

The plan of the paper is as follows. In Section 2, we will present the model and its mathematical structure. In Section 3, we make some simulations and study their results. Specifically, we present the equilibrium distribution of employment and resource which determine the location decisions of firms. In the final Section, we make some concluding remarks and give some ideas for future research. In the Appendix, we present the analytical solution of our model and describe a novel approach for solving numerically second kind Fredholm integral equations systems by using a Taylor-series expansion method which was recently proposed by Maleknejad et al. (2006).

2. The model

We consider a single city located in a line of length S. In other words, 0 and S represent the western and eastern borders of the city. In the city, there is a large number of small identical firms that produce a single good. There are, also, workers who are uniformly distributed and take no location decisions. So, labor is one of the production factors. There are externalities in the production process in the form of positive knowledge spillovers. This means that firms benefit from locating near each other and the total advantage they take depends on the amount of labor used in nearby areas and on the distance between them.

There is a resource available at a given point, in our city, which is also used as a production factor. We assume that the use of the resource generates emissions. So, the government makes firms pay an extra amount of money depending on the total concentration of emissions at each location. Finally, the transportation of the resource is costly. Both of these assumptions - the environmental regulation and the transportation cost - increase the cost of the resource.

The borders of the city under study are strictly defined and firms can locate nowhere else[6]. Our intention is to study the location decisions of firms. More specifically, we aim to consider the equilibrium distribution of employment and resource used in production in order to determine the distribution of firms over sites $r \in [0, S]$.

All firms produce the same traded good using labor, land and a resource. The good is sold around the world at a competitive price assuming no transportation cost. Production *per unit of land* at location $r \in [0, S]$ is given by:

$$f(r) = \exp(\gamma z(r))L(r)^{a}R(r)^{\beta} \tag{1}$$

where f is the goods' production, L is the employment used in production, R is the resource input and $z(r)$ is the production externality, which depends on how many workers are employed at all locations and represents positive knowledge spillovers.

$$z(r) = \int_{0}^{S} \ln(L(s))\ e^{-\delta(r-s)^2} ds \tag{2}$$

The production externality is a positive function of labor 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, the more profitable it is for firms to locate one near the other. When the production externatily plays a major role in location decisions, each firm chooses to locate where all other firms are located. In terms of agglomeration economics, the production externality is a *centripetal* force, ie. a force that promotes spatial concentration of economic activity.

Assume that the resource is available at a point $\bar{r} \in (0, S)$. In other words, $\bar{r}$ is supposed to be an extraction point. It is clear that the point

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

$\bar{r}$ has spatial advantages over other possible locations. If the price of the resource at $\bar{r}$ is p_R, then iceberg transportation costs imply that the price in location r can be written as: $p_R(r) = p_R e^{b(r-\bar{r})^2}$. In other words, if one unit of the resource is transported from $\bar{r}$ to r, only a fraction $e^{-b(r-\bar{r})^2}$ reaches r[7]. So, b is the transportation cost per unit of distance, which is assumed to be positive and finite. Like knowledge spillovers, the transportation cost is a *centripetal* force.

The use of the resource generates emissions. The concentration of emissions X at point r is:

$$X(r) = \phi \int_0^S e^{-\zeta(r-s)^2} \ln(R(s))\, ds \tag{3}$$

where ϕ is a constant implying that aggregate emissions in r are proportional to the amount of the resource used in the neighbourhood of r. Equation (3) also shows that the concentration of emissions at a point r is a weighted average of the resource used in nearby locations. This might capture the movement of emissions in nearby places. A high ζ indicates that only nearby emissions affect the total concentration of emissions at point r.

The cost of environmental policy, $\tau(X(r)),$ (with $\tau' > 0,\ \tau'' \geq 0$) depends on the concentration of emissions at each point and increases the total cost of the resource for the firms. As a result, a firm has to pay $p_R e^{b(r-\bar{r})^2} e^{\tau X(r)}$ for each unit of the resource that uses in the production process. The extra amount of money that a firm pays does not depend only on her own emissions, but on the total emissions at a point r.To put it differently, the higher the concentration of industry at an interval $[s_1, s_2] \in [0, S]$, the higher the cost firms will be obliged to pay. In that way, the environmental policy is a *centrifugal* force, ie. a force that opposes spatial concentration of economic activity.

[7] For a detailed analysis in iceberg costs, see Fujita et al., 1999 and Fujita and Thisse, 2002.

Let w be the real wage rate, which is the same across sites, and let the product price be normalized to one. A firm located at r chooses employment and resource to maximize her profits. Then, the *firm profit per unit of land* gives the equilibrium land rent, $\hat{q}$, at location r, which is equal to:

$$\hat{q}(r) = \max_{L,R} \quad e^{\gamma z(r)} L(r)^a R(r)^\beta - wL(r) - p_R e^{b(r-\bar{r})^2} e^{\tau X(r)} R(r) \qquad (4)$$

If a firm located at r, treats $z(r)$ and $X(r)$ as parameters, then the first order conditions (FOC) for profit maximization are:

$$\begin{aligned} a e^{\gamma z(r)} L(r)^{a-1} R(r)^\beta &= w \\ \beta e^{\gamma z(r)} L(r)^a R(r)^{\beta-1} &= p_R e^{b(r-\bar{r})^2} e^{\tau X(r)} \end{aligned} \qquad (5)$$

The FOC define the optimal distribution of labor and resource at each point $r \in [0, S]$. After taking logs on both sides and doing some transformations (which are described in the Appendix), we obtain a system of second kind Fredholm integral equations with symmetric kernels:

$$\frac{\gamma}{1-a-\beta} \int_0^S e^{-\delta(r-s)^2} y(s) ds - \frac{\tau\phi\beta}{1-a-\beta} \int_0^S e^{-\zeta(r-s)^2} x(s) ds + g_1(r) = y(r) \qquad (6)$$

$$\frac{\gamma}{1-a-\beta} \int_0^S e^{-\delta(r-s)^2} y(s) ds - \frac{\tau\phi(1-a)}{1-a-\beta} \int_0^S e^{-\zeta(r-s)^2} x(s) ds + g_2(r) = x(r) \qquad (7)$$

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

We use a modified Taylor - series expansion method for solving this kind of systems (Maleknejad et al, 2006). More precisely, a Taylor-series expansion can be made for the solutions $y(s)$ and $x(s)$ in the integrals of equations (6) and (7). We use the first two terms of Taylor-series expansion (as an approximate for $y(s)$ and $x(s)$) and substitute them in the integrals of (6) and (7). After some substitutions , which are described in detail in the Appendix, we end up with a linear system of ordinary differential equation of the form:

$$\theta_{11}(r)\ y(r) + \theta_{12}(r)\ y'(r) + \theta_{13}\ y''(r) + \sigma_{11}\ x(r) + \sigma_{12}\ x'(r) + \sigma_{13}\ x''(r) = g_1(r) \tag{8}$$

$$\theta_{21}(r)\ y(r) + \theta_{22}(r)\ y'(r) + \theta_{23}\ y''(r) + \sigma_{21}\ x(r) + \sigma_{22}\ x'(r) + \sigma_{23}\ x''(r) = g_2(r) \tag{9}$$

In order to solve the linear system, we need an appropriate number of boundary conditions. We construct them to obtain a linear system of two algebraic equation that can be solved numerically. This approach provides the following proposition.

Proposition 1: *Equations (6) and (7) have a unique solution as a second kind Fredholm system of integral equations.The solution defines the equilibrium distribution of employment and resource within the spatial domain of our single city. These values depend on the parameters of the model* $(\alpha,\ \beta,\ \delta,\ S,\ \gamma,\ w,\ p_R, b, \hat{r},\ \zeta,\ \tau, \phi)$.

The maximized value of the firm's profit $\hat{q}(r)$, is also the land rent per unit of land that a firm would be willing to pay to operate with these cost and productivity parametres at location r. Since the decision problem at each location is completely determined by the technology level z, the wage rate w, the resource price p_R , the cost of environmental policy τ and the concentration of emissions X, the first order conditions for the maximization problem give us the equilibrium value of labor and the equilibrium amount of the resource used at each location: $L = \hat{L}(z, w, p_R, \tau, X)$ and $R = \hat{R}(z, w, p_R, \tau, X)$. So, the business land rent per unit of land can be written $q = \hat{q}(z, w, p_R, \tau, X)$.

3. Numerical Experiments.

The model of business sector of a sigle city analysed above involves twelve parameters $\alpha,\ \beta,\ \delta,\ S,\ \gamma, w,\ p_R,\ b,\ \hat{r},\ \zeta,\ \tau,\ \phi$. Given these parameters, we can predict the equilibrium pattern of employment, resource and land rents on the given interval. Maps of equilibrium employment and resource-use will determine the location of firms. More precisely, if the distribution of both employment and resource is higher in a central location than in the boundaries, then we expect that the concentration of economic activity will be higher at the centre too.

The map of an equilibrium city will be defined by the two opposing forces already mentioned. On the one hand, there are the production externalities and the resource transportation cost that pull economic activity together and on the other hand, there is the cost of environmental policy that pushes it apart. This trade-off between centripetal and centrifugal forces will determine the geographical structure of the economy. If the transportation cost is high and the positive knowledge spillovers play an important role in the goods production, while the cost of emissions is low, then we may end up in a monocentric economy which promotes the clustering of economic activity. However, when the cost of emissions breaks a certain threshold, the economic activity will be concentrated in two or more regions.

In order to examine all the possible results, we have to give values to the parameters. The share of labor is set to $\alpha = 0.8$ and the share of the resource is $\beta = 0.1$. The length of the city is $S = 2\pi$. In the business sector analysed here, we consider wages as given ($w = 1$) and the same is assumed for the price of the resource which is $p_R = 1$. We also suppose that the resource is available at a point $\hat{r} = \pi$. Finally, the ϕ parameter, which shows how much the amount of the used resource influences the concentration of emissions, is set to $\phi = 2$. To study the economy's possible spatial structure, we can hold the above paremeters constant and vary just the transportation cost, the concentration of emissions, the cost of emissions and the externality parameters.

All figures will be constructed assuming that workers live at their workplaces, as there exists no residentrial sector in our sigle city.

As a benchmark case, we have $\gamma = 0$, $b = 0$ and $\tau = 0$. This means that there is no production externality, no transportation cost for the resource and no environmental policy that increases the cost of the resource. In other words, a firm doen't benefit at all by nearby firms and the per unit cost of the resource is the same at all locations. As expected, Figure 1 shows that the employment is uniformly distributed over the given interval. This means that firms have no incentives to locate in any special point of our economy. So, this curve can show the distribution of economic activity too.

Changing the parameters results in different maps. As we have a lot of parameters in our model, the results we can obtain are a lot too. We will present some interesting cases below which are worth mentioning and expain the structure of the model.

First, we will study some changes in the transportation cost, keeping the other four paremetres as given, ie. $\delta = 0.1$, $\gamma = 0.01$, $\zeta = 0.1$ and $\tau = 0.1$. The value of δ means that firms are strongly influenced by each other, even when the distance between them is substantial. The low value of γ shows that goods production is not strongly affected by production externality. $\zeta = 0.1$ indicates that if a location is polluted then areas in a long distance will be polluted too. The cost of emissions, $\tau = 0.1$, is very low and will change in the following examples.

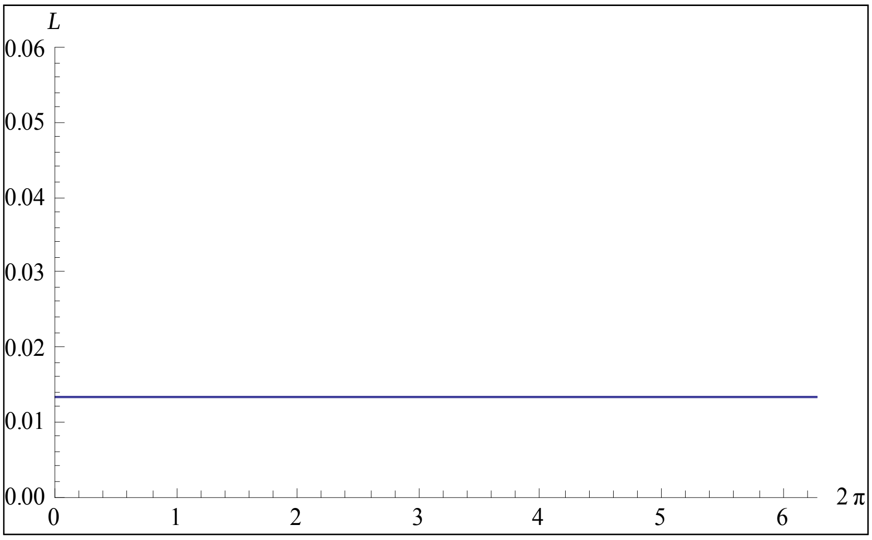

Figure 1: **Employment Distribution** for $\gamma = 0, b = 0$ and $\tau = 0$.

Figures 2 and 3 present employment and resource distributions respectively for different values of transportation cost. Higher transportation costs (blue line) imply higher densities at the point $\hat{r}$ and lower at the boundaries. Consequently, we expect that economic activity will be concentrated at a point close to $\hat{r}$ where the resource is available, so as to avoid the increasing transportation cost near the boundaries. When transportation cost is reduced by one half (from the blue line where $b = 0.2$ to the green one where $b = 0.1$), then at the boundaries, the employment density is twice as much as it is in the first case but it is lower than the centre. Finally, if we decrease the value even more (red line with $b = 0.05$) then the employment is less concentrated as the centripetal force of transportation cost is not strong enough in this case. As far as the density of the resource is concerned, we observe that it is higher at the centre in all cases and it is more concentrated than employment.

Proposition 2: *An increase in the value of transportation cost promotes*

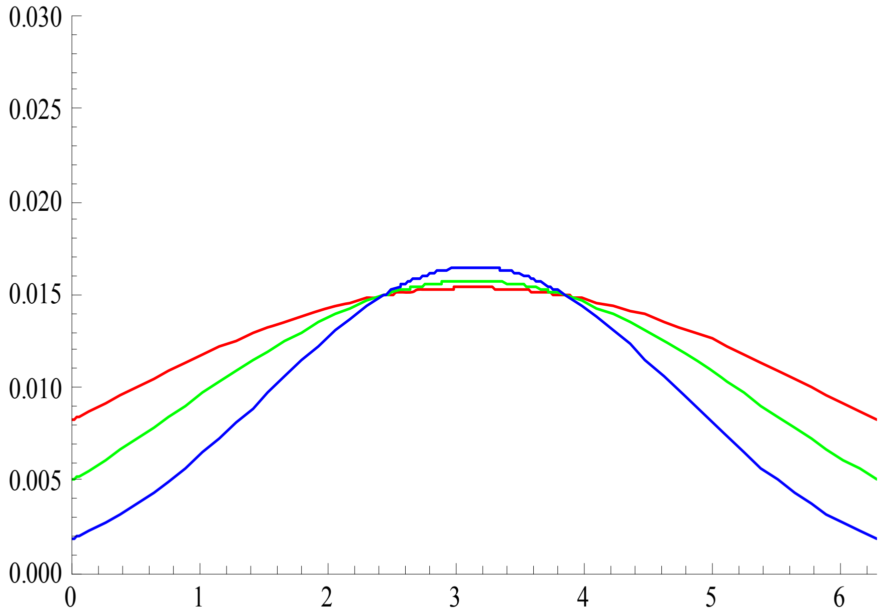

Figure 2: **Employment distribution** for $\delta = 0.1,\ \gamma = 0.01,\ \zeta = 0.1,\ \tau = 0.1$. Changes in Transportation Cost. Red line:$b = 0.05$. Green line:$b = 0.1$. Blue line:$b = 0.2$

the agglomeration of economic activity.

In Fugures 4 and 5, we will study how the employment and resource densities change if we change the value of emission cost. So, we set $\delta = 1,\ \gamma = 0.2,\ \zeta = 0.5$ and $b = 0.1$. The higher value of δ means that the positive knowledge spillovers decline faster with distance. Moreover, the value of γ indicates that goods production is influenced a lot by the production externality. In other words,the centripetal force of production externality is now stronger, and this means that a large number of firms will have an incentive to concentrate in certain areas to benefit from it. On the other hand, the higher value of ζ shows that pollution affects nearby areas, if compared to the first case. Let's study how the environmental policy with respect to the concentration of emissions may affect the clustering of economic activity.

The cost of emissions is a centrifugal force that does not promote the

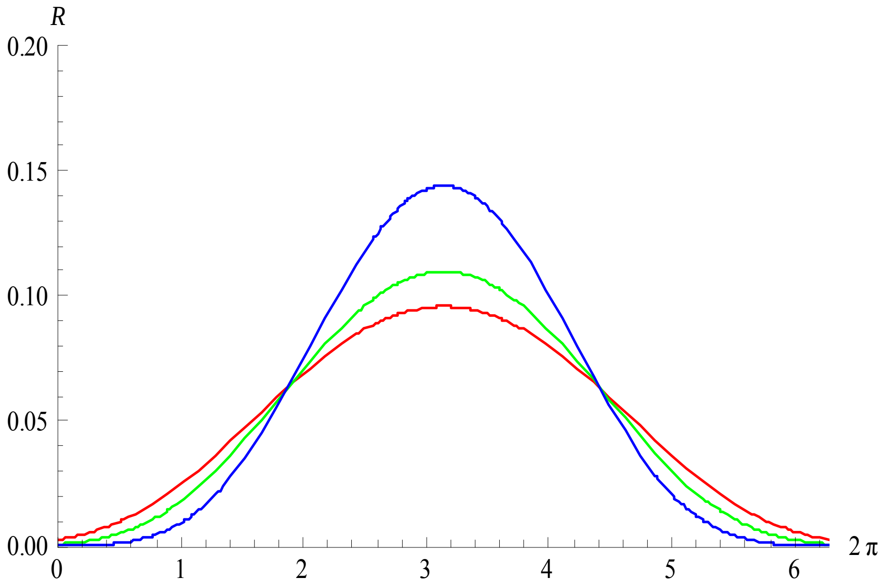

Figure 3: **Resource distribution** for $\delta = 0.1,\ \gamma = 0.01,\ \zeta = 0.1,\ \tau = 0.1.$ Changes in Transportation Cost. Red line:$b = 0.05$. Green line:$b = 0.1$. Blue line:$b = 0.2$

concentration of economic activity. As a result, firms, on the one hand, have an incentive to be concentrated in order to benefit from positive knowledge spillovers, but, on the other hand, they do not locate at the same point because they will be obliged to suffer a higher cost. The trade-off between these opposite forces forms "two peaks". Specifically, there is a high concentration of employment and resource around the points $r = 1$ and $r = 5.2$[8].

Proposition 3: *Under the assumption of strong knowledge spillovers, the enviromental policy may lead to the concentration of economic activity in two "peaks".*

[8]When the cost of emissions increases, the employment density is lower, while the resource density is higher (at some points). There may be some kind of substitution between the two factors of production.

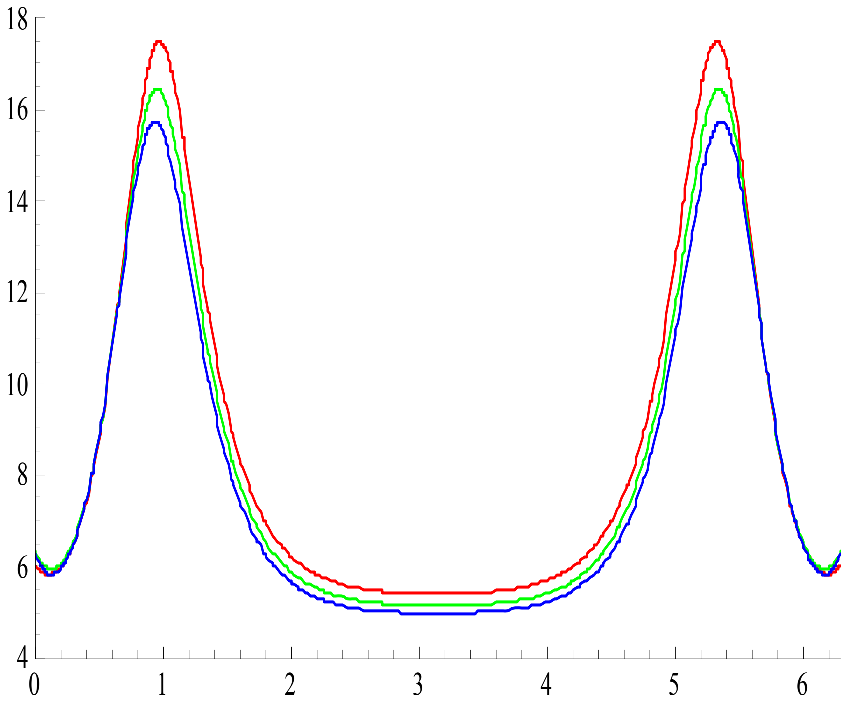

Figure 4: **Employment distribution** for $\delta = 1,\ \gamma = 0.2,\ \zeta = 0.5,\ b = 0.1$. Changes in the cost of emissions. Red line:$\tau = 0.1$. Green line:$\tau = 0.2$. Blue line:$\tau = 0.3$

Figures 6 and 7 present the effects of different values of δ in the employment and resource distribution. There is a high concentration of economic activity at the centre of our single city in all three cases. Specifically, higher values of δ (the blue line with $\delta = 5$) result in a higher peak. A high δ means that workers benefit from positive knowledge spillovers, only when they work near each other. That's why they are more concentrated. When δ takes lower values, there is no need for a high concentration, as knowledge spillovers do not decline so fast with distance. In this simulation, we impose a low cost of emissions, so as to make the centrifugal force weak and be able to study the effects of knowledge spillovers.

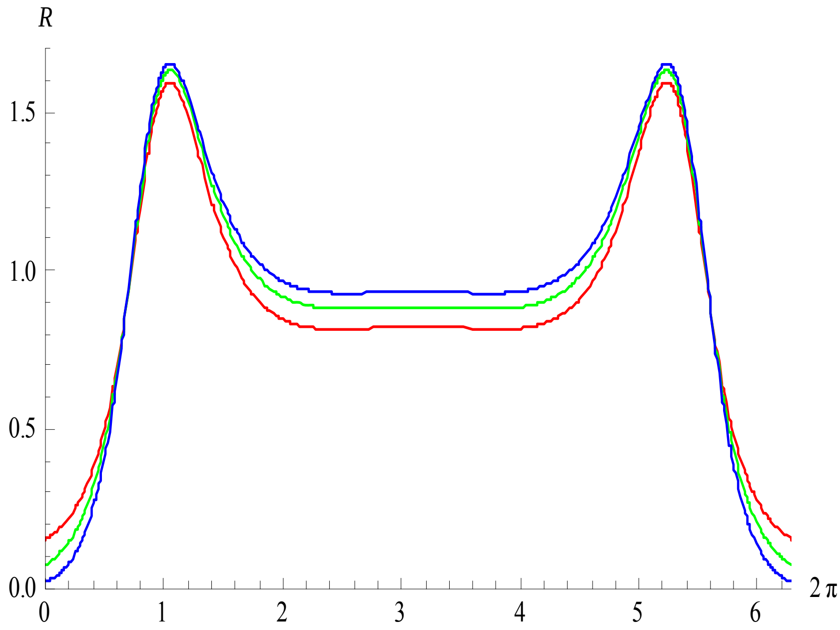

Figure 5: **Resource distribution** for $\delta = 1,\ \gamma = 0.2,\ \zeta = 0.5,\ b = 0.1$. Changes in the cost of emissions. Red line:$\tau = 0.1$. Green line:$\tau = 0.2$. Blue line:$\tau = 0.3$

Proposition 4: *When the positive knowledge spillovers have a stronger effect, the concentration of economic activity is higher.*

In Figure 8 and 9, we consider another set of initial parameters ($\delta = 5, \gamma = 0.1,\ \zeta = 5,\ \tau = 0.2$) and study again some changes in the values of transportation cost. The distribution of employment and resource are totally different from Figures 2 and 3 due to the different initial parameters. More specifically, the high value of δ means that only nearby workers benefit from positive knowledge spillovers. γ is higher too, and as a result, the externality in production is stronger. The higher value of ζ means that pollution affects only neighbourhood areas. Finally, the cost of emissions is twice as much as it was in the first case. So, when the transportation

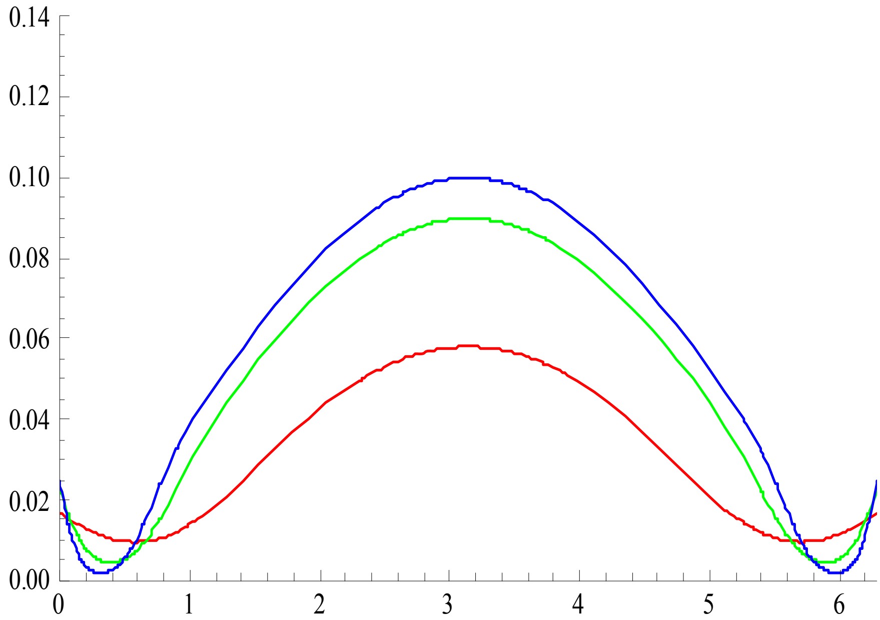

Figure 6: **Employment distribution** for $\gamma = 0.025$, $\zeta = 0.1$, $b = 0.05$, $\tau = 0.1$. Changes in δ. Red line:$\delta = 1$. Green line:$\delta = 3$ Blue line:$\delta = 5$

cost is very low (red line with $b = 0.005$), the centrifugal force of taxation plays an important role in our analysis. As a result, the economic activity is almost uniformly distributed over the interval $r \in (1, 5.2)$, while it is highly concentrated at the boundaries. When the transportation cost increases, we notice that the economic activity starts concentrating both at the centre and at the boundaries, forming three "peaks". Firms which locate close to the point where the resource is available ($r = \hat{r}$), will have to pay a higher cost of emissions - because of the high concentration - but lower transportation cost. As the transportation cost increases, they have an incentive to move closer to $\hat{r}$. When the number of firms that move closer to $\hat{r}$ increases, the pollution at that point increases too and the cost of emissions rises. The result of this "circular process" determines the resource distribution and the

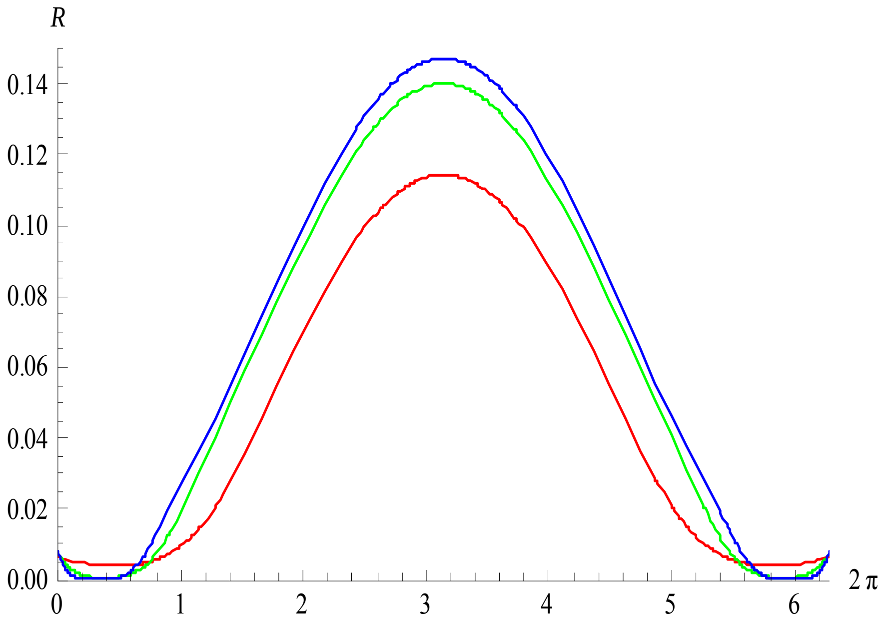

Figure 7: **Resource distribution** for $\gamma = 0.025,\ \zeta = 0.1,\ b = 0.05, \tau = 0.1$. Changes in δ. Red line:$\delta = 1$. Green line:$\delta = 3$ Blue line:$\delta = 5$

location decisions of firms[9].

Proposition 5 : *Under strict environmental policy, the increases in the value of transportation cost promote the agglomeration of economic activity in three points.*

Figures 10 and 11 show the results of another set of parameters ($\delta = 0.4, \gamma = 0.15,\ b = 0.1,\ \tau = 0.2$). We will study the distributions trying the ζ values of $0.01,\ 0.1$ and 1. Increasing the value of ζ means that the concentration of emissions at each point is affected only by nearby emissions.

[9]This circular process determines the pattern we observe in Figures 8 and 9. If the tax didn't increase when the concentration of emissions increases, the higher transportation cost would result in a unique "peak" at the point $r = \hat{r}$.

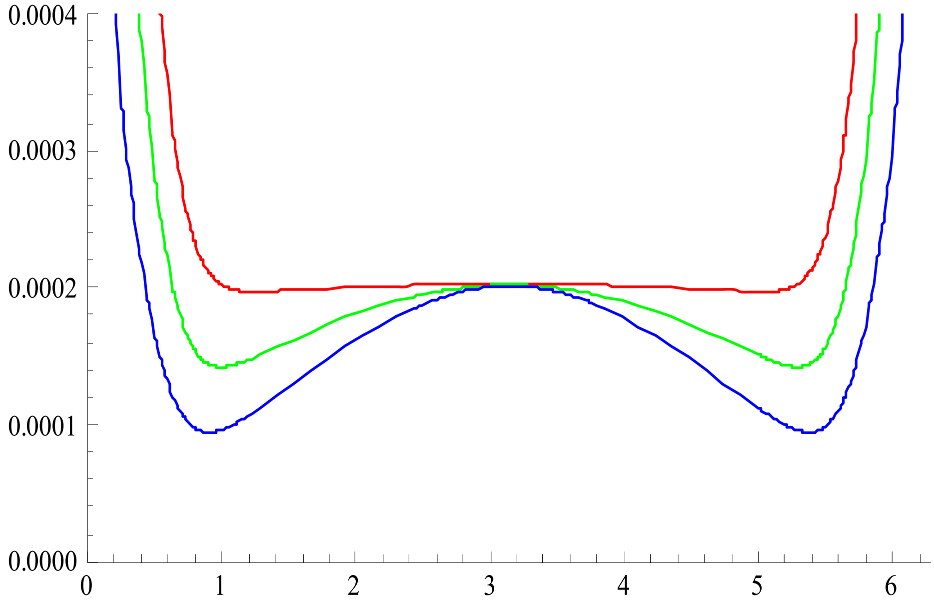

Figure 8: **Employment distribution** for $\delta = 5, \gamma = 0.1$, $\zeta = 5$, $\tau = 0.2$. Changes in transportation cost: Red line: $b = 0.005$. Green line:$b = 0.05$. Blue line:$b = 0.1$

In real world, the value of ζ depends on weather conditions and on natural characteristics of land, such as mountains. As we have assumed that the only dissimilarity in our land is the existence of the resource, we suppose that ζ is influenced only by weather conditions. Specifically, if it is windy, ζ takes a low value, as a lot of areas are polluted by the emissions. As ζ increases, the concentration of emissions in certain areas does not affect other areas so much. Observing the two maps, we conclude that in points $r = 1.6$ and $r = 4.6$ there is a higher concentration of economic activity. However, the distributions of the two factors are not the same[10].

4. Conclusion

[10] As previously stated, there may be some kind of substitution between the two factors, that needs further research.

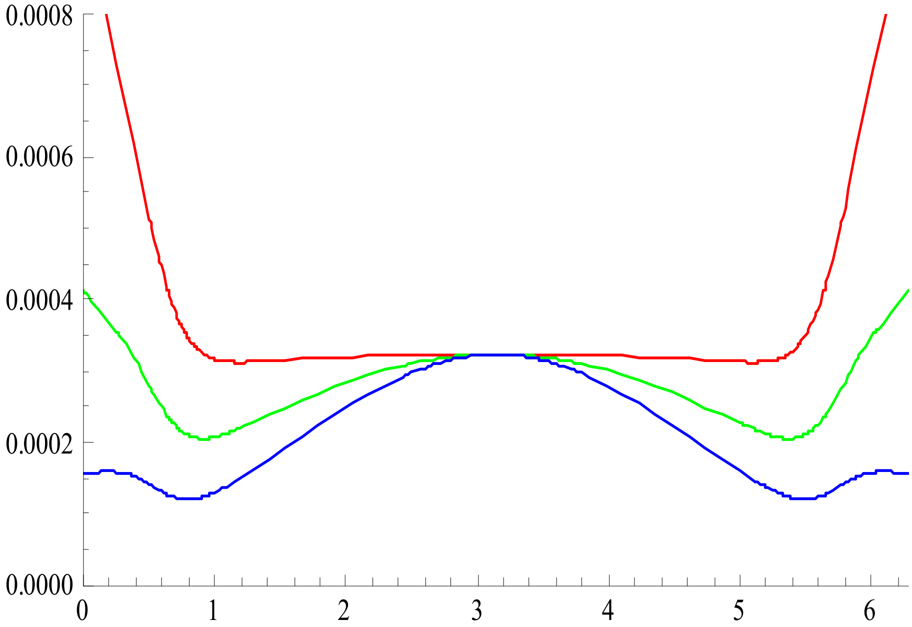

Figure 9: **Resource distribution** for $\delta = 5, \gamma = 0.1$, $\zeta = 5$, $\tau = 0.2$. Changes in transportation cost: Red line: $b = 0.005$. Green line:$b = 0.05$. Blue line:$b = 0.1$

Our model consists of a single city - of length S - a business sector and a natural resource. The city has a nonuniform internal structure because of externalities in production, transportation cost of the resource and environmental policy. Specifically, firms are free to chooze where to locate in the given interval, S, taking into account some facts. First, the employment at each location will be more productive if there is a high concentration of employment at nearby locations. This is the assumption of knowledge spillovers, which is used by Lucas and Rossi-Hansberg (2002). Second, the transportation of the resource is costly and its cost depends on the distance. Finally, the use of the resource generates emissions and the environmental regulator, who plays no role in our model, adapts some kind of environmental policy. The stringence and, therefore, the cost of this policy for the firms is an increasing

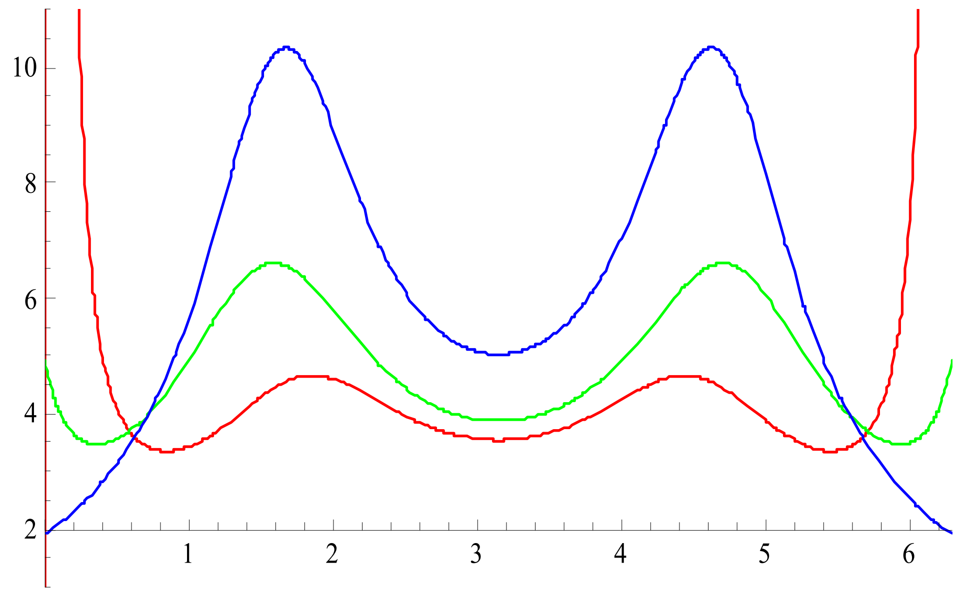

Figure 10: **Employment distribution** for $\delta = 0.4, \gamma = 0.15,\ b = 0.1,\ \tau = 0.2$. Changes in ζ: Red line: $\zeta = 0.01$. Green line:$\zeta = 0.1$. Blue line:$\zeta = 1$

function of aggregate emissions at each spatial point. If all firms decide to locate near the city centre, where the resource is available, they will benefit from positive knowledge spillover and avoid a high transportation cost. So, these forces promote agglomeration. On the other hand, if they locate at that point, the concentration of emissions will be high and they will be obliged to pay a higher cost of emissions. As a result, environmental policy impedes agglomeration. The trade-off of these two forces determines the equilibrium concentration of economic activity.

The results of our analysis are the following. When the external effect is more localized (δ is high), firms have a strong desire to locate near other producers. When the transportation cost of the resource increases, firms move closer to the city centre. Furthermore, when the environmental policy is strict, the distribution of employment and resource becomes flatter. In other words, firms have fewer incentives for agglomeration and concentration

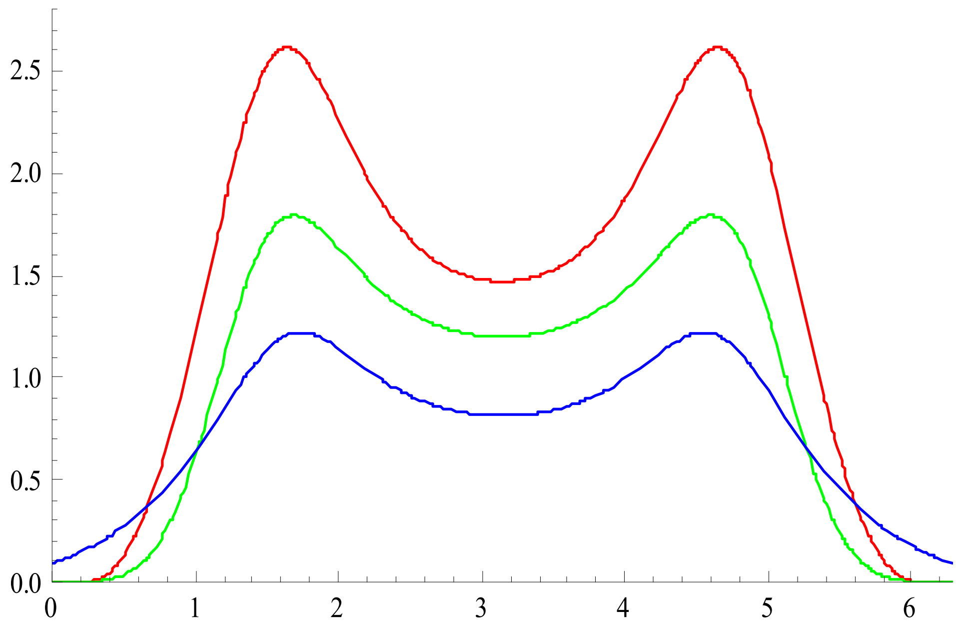

Figure 11: **Resource distribution** for $\delta = 0.4, \gamma = 0.15,\ b = 0.1,\ \tau = 0.2$. Changes in ζ: Red line: $\zeta = 0.01$. Green line:$\zeta = 0.1$. Blue line:$\zeta = 1$

of economic activity.

In this paper, we assumed that people live at their workplaces, having no other choice. The next step in our research will be to change this assumption and study the residential decisions of workers. Workers will consume the produced good, decide where to locate and receive negative utility by the concentration of emissions. Solving workers' problem, we will obtain the residential land rent which can be compared to the business land rent. The comparison will determine the residential and the business areas of our city.

Another possible extension of our model is to study the dynamic problem of the internal stucture of a single city. This can be done by assuming changes in the stock of the resource. In that way, we may be able to explain the structure of cities not only across space, but also across time[11]. These

[11]The theory of optimal control and spatial heterogeneity, analysed by Brock and Xepa-

extensions are left for future research.

Appendix: *Solving systems of second kind Fredholm integral equations.*

The first order conditions of the firm's profit maximazation problem (after taking logs) are equations:

$$\ln a + \gamma \int_0^S e^{-\delta(r-s)^2} \ln(L(s))ds + (a-1)\ln L(r) + \beta \ln R(r) = \ln w \qquad (6)$$

$$\begin{aligned} & \ln \beta + \gamma \int_0^S e^{-\delta(r-s)^2} \ln(L(s))ds + a \ln L(r) + (\beta - 1)\ln R(r) \qquad (7) \\ = \quad & \ln p_R + b(r-\bar{r})^2 + \tau\phi \int_0^S e^{-\zeta(r-s)^2} \ln(R(s))\ ds \end{aligned}$$

Setting $\ln L = y$ and $\ln R = w$, we obtain the following system

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

$$\gamma \int_0^S e^{-\delta(r-s)^2} y(s)ds - \tau\phi \int_0^S e^{-\zeta(r-s)^2} x(s)ds + ay(r) + (\beta-1)x(r)$$

padeas (*Journal of Economic Dynamics and Control, forthcoming*) will help us solve the problem.

$$= \ln p_R + b(r-\bar{r})^2 - \ln\beta$$

We need to do the following transformation in order to obtain a system of second kind Fredholm integral equations with symmetric kernels:

$$\underbrace{\begin{pmatrix} \gamma & 0 \\ \gamma & -\tau\phi \end{pmatrix} \begin{pmatrix} \int_0^S e^{-\delta(r-s)^2} y(s)ds \\ \int_0^S e^{-\zeta(r-s)^2} x(s)ds \end{pmatrix} + \begin{pmatrix} \ln a - \ln w(r) \\ \ln\beta - \ln p_R - b(r-\bar{r})^2 \end{pmatrix}}_{\text{B}} =$$

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

$$B = AZ$$
$$A^{-1}B = Z$$

where $\qquad A^{-1} = \begin{pmatrix} \frac{1-\beta}{1-a-\beta} & \frac{\beta}{1-a-\beta} \\ \frac{a}{1-a-\beta} & \frac{1-a}{1-a-\beta} \end{pmatrix}$

$$\begin{pmatrix} \frac{1-\beta}{1-a-\beta} & \frac{\beta}{1-a-\beta} \\ \frac{a}{1-a-\beta} & \frac{1-a}{1-a-\beta} \end{pmatrix} \left\{ \begin{pmatrix} \gamma & 0 \\ \gamma & -\tau\phi \end{pmatrix} \begin{pmatrix} \int_0^S e^{-\delta(r-s)^2} y(s)ds \\ \int_0^S e^{-\zeta(r-s)^2} x(s)ds \end{pmatrix} + \right.$$

$$\left. \begin{pmatrix} \ln a - \ln w(r) \\ \ln\beta - \ln p_R - b(r-\bar{r})^2 \end{pmatrix} \right\} = \begin{pmatrix} y(r) \\ x(r) \end{pmatrix}$$

$$\begin{pmatrix} \frac{\gamma}{1-\alpha-\beta} & \frac{-\tau\phi\beta}{1-\alpha-\beta} \\ \frac{\gamma}{1-\alpha-\beta} & \frac{-\tau\phi(1-\alpha)}{1-\alpha-\beta} \end{pmatrix} \begin{pmatrix} \int_0^S e^{-\delta(r-s)^2} y(s)ds \\ \int_0^S e^{-\zeta(r-s)^2} x(s)ds \end{pmatrix} +$$

$$\begin{pmatrix} \frac{1-\beta}{1-a-\beta} & \frac{\beta}{1-a-\beta} \\ \frac{a}{1-a-\beta} & \frac{1-a}{1-a-\beta} \end{pmatrix} \begin{pmatrix} \ln a - \ln w(r) \\ \ln\beta - \ln p_R - b(r-\bar{r})^2 \end{pmatrix} = \begin{pmatrix} y(r) \\ x(r) \end{pmatrix}$$

So, the system of second kind Fredholm integral equations is:

$$\frac{\gamma}{1-a-\beta}\int_0^S e^{-\delta(r-s)^2}y(s)ds - \frac{\tau\phi\beta}{1-a-\beta}\int_0^S e^{-\zeta(r-s)^2}x(s)ds + g_1(r) = y(r) \tag{8}$$

$$\frac{\gamma}{1-a-\beta}\int_0^S e^{-\delta(r-s)^2}y(s)ds - \frac{\tau\phi(1-a)}{1-a-\beta}\int_0^S e^{-\zeta(r-s)^2}x(s)ds + \ g_2(r) = x(r) \tag{9}$$

where:

$$g_1(r) = \frac{1}{1-\alpha-\beta}\{(1-\beta)\ (\ln a - \ln w(r)) + \beta(\ln\beta - \ln p_R - b(r-\bar{r})^2)\}$$

$$g_2(r) = \frac{1}{1-\alpha-\beta}\{\alpha(\ln a - \ln w(r)) + (1-\alpha)(\ln\beta - \ln p_R - b(r-\bar{r})^2)\}$$

We use a modified Taylor - series expansion method for solving Fredholm integral equations systems of second kind (Maleknejad et al, 2006)[12]. So, a Taylor-series expansion can be made for the solutions $y(s)$, $x(s)$:

$$y(s) = y(r) + y'(r)(s-r) + \frac{1}{2}y''(r)(s-r)^2$$
$$x(s) = x(r) + x'(r)(s-r) + \frac{1}{2}x''(r)(s-r)^2$$

Substituting them into (8), (9):

$$\frac{\gamma}{1-a-\beta}\int_0^S e^{-\delta(r-s)^2}\left\{y(r) + y'(r)(s-r) + \frac{1}{2}y''(r)(s-r)^2\right\}ds -$$

[12]This approach was first used for solving a class of second kind integral equations by Ren, Zhang and Qiao (1999).

$$\frac{\tau\phi\beta}{1-a-\beta}\int_0^S e^{-\zeta(r-s)^2}\left\{x(r)+x'(r)(s-r)+\frac{1}{2}x''(r)(s-r)^2\right\}ds+g_1(r)=y(r)$$

$$\frac{\gamma}{1-a-\beta}\int_0^S e^{-\delta(r-s)^2}\left\{y(r)+y'(r)(s-r)+\frac{1}{2}y''(r)(s-r)^2\right\}ds-$$

$$-\frac{\tau\phi(1-a)}{1-a-\beta}\int_0^S e^{-\zeta(r-s)^2}\left\{x(r)+x'(r)(s-r)+\frac{1}{2}x''(r)(s-r)^2\right\}ds+\ g_2(r)=x(r)$$

Rewriting the equations we have:

$$\left[1-\frac{\gamma}{1-a-\beta}\int_0^S e^{-\delta(r-s)^2}ds\right]\ y(r)-\left[\frac{\gamma}{1-a-\beta}\int_0^S e^{-\delta(r-s)^2}(s-r)ds\right]\ y'(r)-$$

$$\left[\frac{1}{2}\frac{\gamma}{1-a-\beta}\int_0^S e^{-\delta(r-s)^2}(s-r)^2ds\right]\ y''(r)+\left[\frac{\tau\phi\beta}{1-a-\beta}\int_0^S e^{-\zeta(r-s)^2}ds\right]\ x(r)+$$

$$\left[\frac{\tau\phi\beta}{1-a-\beta}\int_0^S e^{-\zeta(r-s)^2}(s-r)\ ds\right]\ x'(r)+\left[\frac{1}{2}\frac{\tau\phi\beta}{1-a-\beta}\int_0^S e^{-\zeta(r-s)^2}(s-r)^2ds\right]\ x''(r)=g_1(r) \tag{10}$$

$$-\left[\frac{\gamma}{1-a-\beta}\int_0^S e^{-\delta(r-s)^2}ds\right]\ y(r)-\left[\frac{\gamma}{1-a-\beta}\int_0^S e^{-\delta(r-s)^2}(s-r)ds\right]\ y'(r)-$$

$$\left[\frac{1}{2}\frac{\gamma}{1-a-\beta}\int_0^S e^{-\delta(r-s)^2}(s-r)^2 ds\right] y''(r)+\left[1+\frac{\tau\phi(1-a)}{1-a-\beta}\int_0^S e^{-\zeta(r-s)^2} ds\right] x(r)+$$

$$\left[\frac{\tau\phi(1-a)}{1-a-\beta}\int_0^S e^{-\zeta(r-s)^2}(s-r) ds\right] x'(r)+\left[\frac{1}{2}\frac{\tau\phi(1-a)}{1-a-\beta}\int_0^S e^{-\zeta(r-s)^2}(s-r)^2 ds\right] x''(r) = g_2(r) \tag{11}$$

If the integrals in equations (10), (11) can be solved analytically, then the bracketed quantities are functions of r alone. So (10), (11) become a linear system of ordinary differential equations that can be solved, if we use an appropriate number of boundary conditions.

To manufacture boundary conditions we differentiate (8) & (9):

$$y'(r) = \frac{\gamma}{1-\alpha-\beta}\int_0^S -2\delta\ (r-s)\ e^{-\delta(r-s)^2}\ y(s)\ ds$$

$$-\frac{\tau\phi\beta}{1-\alpha-\beta}\int_0^S -2\zeta\ (r-s)\ e^{-\zeta(r-s)^2}\ x(s)\ ds + g_1'(r) \tag{12}$$

$$y''(r) = \frac{\gamma}{1-\alpha-\beta}\int_0^S \left[-2\delta+4\delta^2\ (r-s)^2\right]\ e^{-\delta(r-s)^2}\ y(s)\ ds$$

$$-\frac{\tau\phi\beta}{1-\alpha-\beta}\int_0^S \left[-2\zeta+4\zeta^2\ (r-s)^2\right]\ e^{-\zeta(r-s)^2}\ x(s)\ ds + g_1''(r) \tag{13}$$

$$x'(r) = \frac{\gamma}{1-\alpha-\beta}\int_0^S -2\delta\ (r-s)\ e^{-\delta(r-s)^2}\ y(s)\ ds$$

$$-\frac{\tau\phi(1-\alpha)}{1-\alpha-\beta}\int_0^S -2\zeta\ (r-s)\ e^{-\zeta(r-s)^2}\ x(s)\ ds + g_2'(r) \tag{14}$$

$$x''(r) = \frac{\gamma}{1-\alpha-\beta}\int_0^S \left[-2\delta + 4\delta^2\ (r-s)^2\right]\ e^{-\delta(r-s)^2}\ y(s)\ ds$$

$$-\frac{\tau\phi(1-\alpha)}{1-\alpha-\beta}\int_0^S \left[-2\zeta + 4\zeta^2\ (r-s)^2\right]\ e^{-\zeta(r-s)^2}\ x(s)\ ds + g_2''(r) \tag{15}$$

We substitute $y(r)$ and $x(r)$ for $y(s)$ and $x(s)$ in the integrals in equations (12)-(15) to obtain:

$$\mathbf{y}'(\mathbf{r}) = \left[\frac{\gamma}{1-\alpha-\beta}\int_0^S -2\delta\ (r-s)\ e^{-\delta(r-s)^2}\ ds\right]\ \mathbf{y}(\mathbf{r})$$

$$-\left[\frac{\tau\phi\beta}{1-\alpha-\beta}\int_0^S -2\zeta\ (r-s)\ e^{-\zeta(r-s)^2}\ ds\right]\ \mathbf{x}(\mathbf{r}) + g_1'(r) \tag{16}$$

$$\mathbf{y}''(\mathbf{r}) = \left[\frac{\gamma}{1-\alpha-\beta}\int_0^S \left[-2\delta + 4\delta^2\ (r-s)^2\right]\ e^{-\delta(r-s)^2} ds\right]\ \mathbf{y}(\mathbf{r})$$

$$-\left[\frac{\tau\phi\beta}{1-\alpha-\beta}\int_0^S \left[-2\zeta + 4\zeta^2\ (r-s)^2\right]\ e^{-\zeta(r-s)^2}\ ds\right]\ \mathbf{x}(\mathbf{r}) + g_1''(r) \tag{17}$$

$$\mathbf{x}'(\mathbf{r}) = \left[\frac{\gamma}{1-\alpha-\beta}\int_0^S -2\delta\ (r-s)\ e^{-\delta(r-s)^2}\ ds\right]\ \mathbf{y}(\mathbf{r})$$

$$-\left[\frac{\tau\phi(1-\alpha)}{1-\alpha-\beta}\int_0^S -2\zeta\ (r-s)\ e^{-\zeta(r-s)^2}\ ds\right]\ \mathbf{x}(\mathbf{r})+g_2'(r) \tag{18}$$

$$\mathbf{x}''(\mathbf{r})=\left[\frac{\gamma}{1-\alpha-\beta}\int_0^S \left[-2\delta+4\delta^2\ (r-s)^2\right]\ e^{-\delta(r-s)^2}\ \ ds\right]\ \mathbf{y}(\mathbf{r})$$

$$-\left[\frac{\tau\phi(1-\alpha)}{1-\alpha-\beta}\int_0^S \left[-2\zeta+4\zeta^2\ (r-s)^2\right]\ e^{-\zeta(r-s)^2}\ ds\right]\ \mathbf{x}(\mathbf{r})+g_2''(r) \tag{19}$$

$>$From eq (16)-(19), $y'(r)$, $y''(r)$, $x'(r)$, $x''(r)$ are functions of $y(r)$, $x(r)$, $g_1'(r)$, $g_1''(r)$, $g_2'(r)$, $g_2''(r)$. Substituting them into (10) & (11), we have a linear system of two algebraic equations that can be solved easily using Mathematica.

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