2020/15

DP

Sergey Kichko, Wen-Jung Liang, Chao-Cheng Mai, Jacques-François Thisse and Ping Wang

The rise (and fall) of science parks

CORE
CENTER FOR OPERATIONS RESEARCH AND ECONOMETRICS

CORE
Voie du Roman Pays 34, L1.03.01
B-1348 Louvain-la-Neuve
Tel (32 10) 47 43 04
Email: immaq-library@uclouvain.be
https://uclouvain.be/en/research-institutes/lidam/core/discussion-papers.html

The Rise (and Fall) of Science Parks

Sergey Kichko, HSE University   Wen-Jung Liang, National Dong Hwa University

Chao-Cheng Mai, Academia Sinica and Tamkang University

Jacques-François Thisse, CORE-Université catholique de Louvain, HSE University and CEPR

Ping Wang, Washington University in St. Louis and NBER

April 14, 2020

Abstract: Science parks play a growing role in knowledge-based economies by accommodating high-tech firms and providing an environment that fosters location-dependent knowledge spillovers and promote R&D investments by firms. Yet, not much is known about the economic conditions under which such entities may form in equilibrium *without* government interventions. This paper develops a spatial equilibrium model with a competitive final sector and a monopolistically competitive intermediate sector, which allows us to determine necessary and sufficient conditions for a science park to emerge as an equilibrium outcome. We show that strongly localized knowledge spillovers, skilled labor abundance, and low commuting costs are key drivers for a science park to form. Not only is the productivity of the final sector higher when intermediate firms cluster, but a science park hosts more intermediate firms, more researchers and more production workers, and yields greater worker welfare, compared to a counterfactual flat city. With continual improvements in infrastructure and communication technology that lowers coordination costs, science parks will eventually be fragmented. (JEL Classification Numbers: D51, L22, O33, R13.)

Keywords: science park, knowledge spillovers, intermediate firm clustering, land use, worker commuting, R&D.

Acknowledgments: We are grateful for comments by M. Berliant, M. Fujita, S. Peng, E. Rossi-Hansberg, and participants at the Midwest Economic Theory Meeting, North American Regional Science Association Meeting, and the Society for Advanced Economic Theory Conference. Financial support from Academia Sinica, the National Science Council, Tamkang University, the Russian Science Foundation under the grant N°18-18-00253, and the Weidenbaum Center on the Economy, Government, and Public Policy to enable this international collaboration is gratefully acknowledged for funding an early version of this project, CEPR DP13568. We are saddened that the third author passed away during the research collaboration process. The usual disclaimer applies.

Correspondence: J.-F. Thisse, CORE, Université catholique de Louvain; jacques.thisse@uclouvain.be

1 Introduction

The concept of *science park* seems to have gained the favor of many analysts and policy-makers (see, e.g., Katz and Bradley, 2013). Even though the idea of industrial district has been around for a long time (Marshall, 1890, ch. X), it was not until the 1980s that the related concept of science park has been developed (Castells and Hall, 1994; Saxenian, 1994). As emphasized by Saxenian (1994, pp. 32-33 and 118-119), many firms (such as those in the Information and Communications Technology, or in short ICT, industry) clustering in the Silicon Valley produce high-tech intermediate goods and make big R&D investments, which are beneficial to all firms because ideas and knowledge can be transferred more quickly and seamlessly through various channels.[1]

There is a rich variety of science parks, which is well illustrated by the many histories of parks (McCarthy *et al.*, 2018). However, they do share some common features that may be used to build an economic theory of science park. First of all, a science park is primarily designed (i) to accommodate high-tech firms, including particularly interrelated *intermediate firms* at various production stages, (ii) to provide an environment that fosters location-dependent *knowledge spillovers*, and (iii) to encourage *R&D investments by firms*, while researchers and high-skilled workers can be drawn from nearby universities/research institutes. A science park also offers an opportunity to its workers, for earning higher wages by involving in research and production activities in a productive high-tech environment.

In addition, a science park functions as a real estate provider developing and renting office and lab space, as well as housing, retail, restaurants and other leisure facilities within a given geographic area. A science park thus offers an *urban environment* to its population (Katz and Bradley, 2013; McCarthy *et al.*, 2018). This leads us to consider a science park as a city whose center is determined endogenously by the interaction between multiple stakeholders through the above-mentioned channels. In summary, there are both specific demand and supply forces at work in the formation of a science park. These are the forces we consider in this paper.

Despite the importance of science parks in the real world (see, e.g., Link and Scott, 2003, for documenting the historical growth of U.S. science parks), it is fair to say that this concept has attracted little attention in economic theory (Link and Scott, 2007). This is where we hope to contribute by providing a full-fledged general equilibrium model that allows

[1] See Arzaghi and Henderson (2008), Buzart *et al.* (2017) and Greenstone *et al.* (2010), as well as critical reviews by Audretsch and Feldman (2004) and Carlino and Kerr (2015).

us to determine under which conditions a science park emerges as a *decentralized equilibrium outcome*. It is our belief that our setting will contribute to a better understanding of the formation of science parks and will allow for a more precise quantification of their economic consequences and a better evaluation of relevant policies.

To achieve our goal, we develop a model that captures the following basic features: (i) a composite consumption good is produced by using an endogenous range of specialized inputs provided by intermediate firms whose combination generates coordination problems that requires the hiring of production-line designers; (ii) workers are also hired to produce intermediate goods or to conduct R&D in the intermediate sector; (iii) the productivity of an intermediate firm depends on its level of R&D investments and inter-firm spillovers, the intensity of which depends on how intermediate firms are distributed across space; and, (iv) both workers and intermediate firms are spatially mobile and use land. Firms' R&D investments and the existence of knowledge spillovers determine the agglomeration force. On the other hand, the clustering of firms increases the average commuting distance of workers which, in turn, gives rise to higher wages and land rent within the cluster. In sum, the dispersion force is generated by both intermediate firms' and workers' demand for land and costly commuting for skilled workers. The equilibrium distribution of firms and workers is determined as the balance between these two opposite forces that in turn determines the formation and the size of a science park.

The main tenet of this paper is that *the emergence and efficiency of a science park is intimately related to the spatial structure of the area that hosts it.* More specifically, we view a science park as a spatial cluster formed by firms which interact to determine endogenously the intensity of knowledge spillovers. Such a city structure accommodates the largest number of researchers and the highest level of R&D. Recall that the clustering of firms is also associated with other agglomeration economies, such as a large pool of high-skilled and specialized workers and the provision of knowledge-intensive business services and sophisticated infrastructures, which enhances firms' productivity.[2] To understand better how these various forces interact to give rise to a science park, we consider the other extreme of the spectrum, i.e., a city where activities are dispersed across locations and the level of R&D is low. Specifically, we determine the conditions under which a science park is formed and compare it with a flat city where all firms and workers reside uniformly. Such a comparison enables us to gain better insight toward understanding the benefit from the emergence of a science park.

[2]For surveys, see Duranton and Puga (2004), Rosenthal and Strange (2004), and Combes and Gobillon (2015).

Our main results are summarized as follows. We begin by establishing necessary and sufficient conditions for a science park to emerge as a spatial equilibrium outcome. This in turn will allow us to uncover the reasons explaining why science parks may or may not be formed. In particular, we identify three key rationales for firms to have incentives for clustering in a science park: (i) *more localized knowledge spillovers*, (ii) *relatively inexpensive costs of commuting*, and (iii) *abundance of skilled labor*. These are all typical features of new high-tech industries that make a science park, which accommodates more intermediate firms and fosters research activities, more likely to emerge. This may explain why such firms are often clustered in science parks such as the Silicon Valley, the Hsinchu Science-Based Industrial Park in Taiwan or the Cambridge Science Park in the U.K. (Saxenian, 1994; Chen, 2008; Helmers, 2019) and why in the absence of localized knowledge spillovers, simple cluster policies are not sufficient for a science park or a local innovative system to develop (see Duranton *et al.*, 2010, for a critical appraisal of such policies). Although our analysis of spatial externalities remains relatively rudimentary, our paper may be viewed as an attempt to open the black box of spatial externalities by means of a setting that take firms' behavior as the driving force.

We also show that abundant availability of skilled workers fosters a larger science park if one emerges, whereas more localized spillovers leads to a smaller science park but makes it more likely to arise in equilibrium. Moreover, continual improvements in infrastructure and communication technology that lowers coordination costs may lead to the fragmentation of science parks as observed in the case of Silicon Valley (Saxenian, 1994). Moreover, by comparing with a counterfactual flat city, we find that *city with a science park hosts more intermediate firms, more researchers and more production workers*, but fewer designers. Furthermore, the final sector is more productive while *wages and land rents are higher in a science park than in a flat city.* Despite paying higher rent and incurring higher commuting costs, we show that workers are better off in a science park than in a flat city.

Yet, science parks should not be viewed as the panacea for local development. Since they offer high wages, they attract high-skilled workers. Eventually, too large an inflow of migrants will lead to their geographical fragmentation. Indeed, high land rents and commuting costs become a concern to potential entry of small specialized firms. More specifically, we will see that *science parks are more likely to be sustainable in urban environments that do not have too large a labor pool.* This may explain why most successful science parks do not emerge in megacities. For example, Silicon Valley is over 30 miles south of San Francisco, the Cambridge Science Park in the U.K. more than 60 miles north of London, and Hsinchu Science-Based

Industrial Park in Taiwan 50 plus miles away from Taipei.

Related literature. A handful of related models have been developed in urban economics. Their common aim is to explain the emergence of business centers within cities. They include O'Hara (1977), Ogawa and Fujita (1980), Fujita and Ogawa (1982), Berliant *et al.* (2002), and Lucas and Rossi-Hansberg (2002). However, these models focus on gravity-like reduced forms in which knowledge spillovers and/or spatial externalities are mechanically presumed. They ignore firms' R&D policies and the supply of intermediate inputs and knowledge-intensive business services, which affect the overall productivity of firms. Although spatial externalities have attracted a lot of attention in urban economics (see Carlino and Kerr, 2015, for a survey), we are not aware of a microeconomic model developed to investigate how spatial externalities emerge from intentional firms' R&D and location decisions. Here it is worth mentioning Desmet and Rossi-Hansberg (2014) who study how firms choose to innovate in a dynamic setting characterized by spatial frictions. However, unlike us, they cannot characterize the equilibrium analytically, so that they have to source to quantitative analysis.

The remainder of the paper is organized as follows. The model is presented in Section 2, while Section 3 describes the optimizing conditions of the different groups of agents. The necessary and sufficient conditions for a science park to emerge are determined and its properties are studied in Section 4. In Section 5, we undertake a theoretical counterfactual by comparing a science park and a flat city where firms are workers are fully mixed. Section 6 concludes.

2 The model

To focus on the formation of a science park, we shall consider a very simple demand structure and outside option just to suit the need for closing the model. Specifically, the economy consists of (i) a featureless one-dimensional space Z named as a high-tech city and (ii) an outside world, called the rest of the world (ROW). The high-tech city is populated by a continuum H of skilled workers. There is also a continuum $U \gg H$ of unskilled workers who can only perform a cottage production in the ROW. There is a single homogeneous final good, chosen as the numéraire, that can be produced in the high-tech city using an endogenous array of intermediate inputs, or alternatively produced in ROW under a linear technology ψU, where ψ is assumed sufficiently small to capture the low efficacy of cottage production. Since our focus is on the intermediate sector, it is convenient to assume that the final producers do not consume land. By contrast, production of intermediate goods in the high-tech city requires land that is owned by absentee landlords or a local government, where land density and the opportunity cost of land are normalized to one.

Workers are used to enhance the efficiency of the intermediate sector by performing the following three tasks: (i) to undertake firm-specific R&D, (ii) to design the production line in the final sector, and (iii) to produce intermediate goods. A unit mass of firms are able to produce the final good with the basket of intermediate goods, which is priced under perfect competition, consistent with the outside option of cottage production. Intermediate firms and workers chose their location within the urban area and consume a fixed amount of land normalized to one. The final and intermediate goods are shipped within the city at no costs, thus implying that the prices of intermediate goods are independent of where intermediate and final producers are located. Dealing with shipping costs is fairly straightforward and does not add much to our results. In line with urban economics, assuming that the final sector is located at the city center allows us to focus on symmetric distributions of intermediate firms and workers. Using another location for the final sector does not affect the nature of our main results, but would render the formal analysis more cumbersome.

Apart from land, workers consume the final good. Each worker is endowed with one unit of labor that she supplies inelastically. Commuting between the residence $y \in Z$ and workplace $z \in Z$ requires $t\,|y - z|$ units of the numéraire, where $t > 0$ is the commuting rate.

2.1 The spatial structure of the economy

In this paper we focus on the high-tech city where all firms are clustered, which is flanked by two residential areas. Following the literature, we assume that the high-tech city is geographically symmetric and centered at $z = 0$. Since each worker and each firm consumes one unit of land, the total demand for land is equal to $N + H$ where N is the mass of intermediate firms that will be endogenously determined in equilibrium. Therefore, the city is given by the interval

$$Z = \left[-\frac{N+H}{2}, \frac{N+H}{2}\right],$$

which implies that the city size varies with the mass of intermediate firms (N) and the population size (H). As will be seen, the size of a high-tech city depends on the way the intermediate sector is spatially organized.

The intermediate producers are uniformly distributed within the science park whose spatial extend is given by

$$Z^F = [-N/2, N/2],$$

with density $h^F = 1$. Workers are uniformly distributed over the residential area

$$Z^W = \left[-\frac{N+H}{2}, -\frac{N}{2}\right] \cup \left[\frac{N}{2}, \frac{N+H}{2}\right]$$

with density $h^W = 1$.

2.2 The intermediate sector

The intermediate sector produces differentiated intermediate goods under monopolistic competition and decreasing returns. Each intermediate is provided by a single firm and each firm supplies a single intermediate good. Since a firm located at z makes the same choices in equilibrium regardless of the variety it produces, we index intermediate inputs by their place of production z.

A firm located at $z \in Z^F$ produces the intermediate good $z \in [-N/2, N/2]$ and uses one unit of land, $R(z)$ units of labor for R&D, and $L(z)$ units of labor for production. This firm produces the quantity $x(z)$ according to a Cobb-Douglas technology:

$$x(z) = A(z) \cdot L(z)^{\beta} l^{1-\beta} \tag{1}$$

with $\beta \in (0, 1)$ and $l = 1$.

The total factor productivity (TFP) of an intermediate firm $A(z)$ is given by a Cobb-Douglas aggregator of the firm's R&D employment $R(z)$ and a *spatial externality* that combines a Romer-Lucas external effect weighted by a distance-decay function $S(z)$:

$$A(z) = R(z)^{\theta} \cdot (\bar{R}S(z))^{1-\theta}, \tag{2}$$

where $\bar{R}$ is the total mass of workers involved in R&D activities, $S(z)$ is a measure of firms' spatial concentration around z, and $\theta \in (0, 1)$. Our setup of the endogenous TFP captures Romer's idea that externalities enter the system through an aggregator of individual firms' decisions, but we recognize that a firm's TFP is also influenced by this firm's R&D policy.

One of the distinctive features of our setting is that a firm's TFP is endogenized through the following three channels: (i) the number of researchers hired to conduct R&D in each firm, (ii) the total number of researchers working the economy, and (iii) the spatial distribution of firms/researchers. This modeling strategy is consistent with the idea that spillovers increase the level and productivity of R&D investments (Aghion and Jaravel, 2015; Helmers, 2019). It is also in line with Chyi *et al.* (2012) who find that knowledge spillovers are especially strong across intermediate firms located in science parks. That said, it is worth stressing that *what distinguishes a science park is the presence of the endogenous R&D shifter* $R^{\theta}\bar{R}^{1-\theta}$ *in* (2). In this context, the efficiency of an intermediate firm depends on its level of R&D activities, as well as on the total mass of researchers whose productivity rises with their number (this was highlighted by Romer, 1986, and Lucas, 1988). While the urban economics literature highlights the existence of various types of agglomeration economies, the impact of the spatial structure on the endogenous R&D shifter $R^{\theta}\bar{R}^{1-\theta}$ is often overlooked although its importance is stressed by empirical evidence (e.g., Siegel *et al.,* 2003).

In (2), the spatial externality at z is generated by both the size of the research pool in the intermediate sector ($\bar{R}$) and the spatial distribution of intermediate firms ($S(z)$). In line with the literature, we assume that the distance-decay effect is given by a negative exponential (Fujita and Ogawa, 1982; Lucas and Rossi-Hansberg, 2002; Desmet and Rossi-Hansberg, 2014; de Palma *et al.*, 2019):

$$S(z) \equiv \int_{-N/2}^{N/2} \exp(-\gamma\,|z-y|)h^F \mathrm{d}y = \frac{1}{\gamma}\left[2 - \mathrm{e}^{-\gamma N/2}\left(\mathrm{e}^{-\gamma z} + \mathrm{e}^{\gamma z}\right)\right] \tag{3}$$

since $h^F = 1$. Admittedly, $S(z)$ has the nature of a reduced-form that aims to capture a rich set of interactions. In this respect, we want to stress that Smith (1978) has provided some micro-foundations for (3) that went unnoticed. He shows that, when knowledge flows are drawn randomly, the distance-decay function that describes the spatial diffusion of knowledge across space is given by a negative exponential if and only if a low-cost knowledge flow between two locations is more likely to be observed than a high-cost flow. Whereas $S(z)$ decreases with the spatial impedance parameter γ that measures the severity of distance-decays of positive spatial externality, it increases at a decreasing rate with the mass of intermediate firms N that gives rise to an agglomeration force encouraging firm clustering. Note also that $S(z)$ is strictly decreasing and concave in z.

Since workers bear commuting costs, the equilibrium wage rate $w(z)$ is location-specific. The immobility of land implies that the land rent $r(z)$ is also location-specific. Taking wages and land rents as given, each firm chooses its location z, output price $p(z)$, and the numbers of workers allocated to its production and R&D activities to maximize profits:

$$\pi(z) = p(z)x(z) - w(z)\left[R(z) + L(z)\right] - r(z). \tag{4}$$

The land rent $r(z)$ plays the role of an endogenous and location-specific fixed cost for an intermediate firm located at z. If land were not an input of the intermediate sector, the mass of firms under free entry would not be finite for firms operate under decreasing returns, which is in accordance with Desmet and Rossi-Hansberg (2012).

2.3 The final sector

For any given N, the final sector in the high-tech city produces the numéraire according to the following production function:

$$Y = \int_{Z^F} x(z)^{\frac{\sigma-1}{\sigma}} \mathrm{d}z, \tag{5}$$

where $\sigma > 1$. Furthermore, designing the production line gives rise to an expenditure that has the nature of an endogenous fixed cost for the final sector. This cost accounts for the fact that combining specialized and differentiated inputs (or tasks) tends to generate specific coordination costs that grow as the number of inputs increases (cf. Becker and Murphy, 1992). We allow final production to exhibit decreasing returns to scale so that coordination costs can be covered.

Taking both the wage rates and the prices of intermediate goods as given, the final sector located at $z = 0$ maximizes profits given by

$$\Pi = Y - \int_{Z^F} p(z)x(z)\mathrm{d}z - w(0)\phi N, \tag{6}$$

subject to (5). In this expression, $w(0)\phi N$ stands for the coordination costs incurred by the final producers when production involves N differentiated inputs, while $\phi > 0$ is the labor requirement needed to use one additional intermediate input.

2.4 Workers

Each worker chooses her residential site y and workplace z. Since workers' utility is increasing in the final good consumption, maximizing consumption amounts to maximizing her net income given by

$$\max_{y,z} I(y,z) = w(z) - t|y-z| - r(y). \tag{7}$$

At the residential equilibrium, workers reach the same utility level, hence earn the same net income I_0:

$$I(y,z) = I_0, \tag{8}$$

where I_0 is endogenous. This condition implies that a worker has no incentive to change either her residential or working places.

Labor is allocated to the following three activities: (i) the mass $M \equiv \phi N$ of workers involved in designing the supply chain of the final sector, (ii) the mass $\bar{R}$ of workers involved in R&D activities, and (iii) the mass $\bar{L}$ of workers producing the intermediate goods. Labor market clearing implies the following condition:

$$H = M + \bar{R} + \bar{L}. \tag{9}$$

3 The programs of firms and workers

In this section, we determine the equilibrium conditions for the final and intermediate producers, as well as for workers.

3.1 The final sector

The final sector chooses the mass N of intermediate goods and the quantity x of each variety. Since shipping the intermediate goods to the final sector is costless, the price of an intermediate good i is the same within the city. Therefore, plugging (5) in (6) and differentiating Π yields the profit-maximization conditions:

$$\begin{aligned} \frac{\mathrm{d}\Pi}{\mathrm{d}x} &= \frac{\sigma - 1}{\sigma} x(z)^{-\frac{1}{\sigma}} - p(z) = 0, \\ \frac{\mathrm{d}\Pi}{\mathrm{d}N} &= x(N/2)^{\frac{\sigma-1}{\sigma}} - w(0)\phi - p(N/2)x(N/2) = 0, \end{aligned} \tag{10}$$

because the marginal variety N is produced at the edge of the cluster $N/2$. Thus, the final sector's inverse demand for the variety produced at z is location-specific and given by

$$p(z) = \frac{\sigma - 1}{\sigma} x(z)^{-\frac{1}{\sigma}}. \tag{11}$$

Using (11), we obtain the output of a firm located at the edge of the cluster:

$$x(N/2)^{\frac{\sigma-1}{\sigma}} = \sigma w(0)\phi. \tag{12}$$

3.2 The intermediate sector

Plugging (11) and (1) into (4) yields the following profit function:

$$\pi(z) = \left[R(z)^{\theta} \cdot (\bar{R}S(z))^{1-\theta} \cdot L(z)^{\beta}\right]^{\frac{\sigma-1}{\sigma}} - w(z)\left[R(z) + L(z)\right] - r(z). \tag{13}$$

Applying the first-order conditions with respect to $R(z)$, $L(z)$, and z leads to the following equations:

$$\theta \left(\frac{\sigma-1}{\sigma}\right)^2 \cdot R(z)^{\frac{\theta(\sigma-1)}{\sigma}-1} \cdot \left[(\bar{R}S(z))^{1-\theta} \cdot L(z)^{\beta}\right]^{\frac{\sigma-1}{\sigma}} = w(z),$$

$$\beta \left(\frac{\sigma-1}{\sigma}\right)^2 \cdot \frac{1}{L(z)} \cdot \left[(\bar{R}S(z))^{1-\theta} \cdot L(z)^{\beta}\right]^{\frac{\sigma-1}{\sigma}} = w(z),$$

$$\begin{aligned} &(1-\theta) \left(\frac{\sigma-1}{\sigma}\right)^2 \cdot \frac{1}{S(z)} \cdot \left[(\bar{R}S(z))^{1-\theta} \cdot L(z)^{\beta}\right]^{\frac{\sigma-1}{\sigma}} \cdot \frac{\mathrm{d}S(z)}{\mathrm{d}z} \\ = \ &\frac{\mathrm{d}w(z)}{\mathrm{d}z} \cdot [R(z) + L(z)] + \frac{\mathrm{d}r(z)}{\mathrm{d}z}. \end{aligned}$$

Simplifying, we obtain:

$$w(z) = \theta \left(\frac{\sigma-1}{\sigma}\right)^2 \frac{1}{R(z)} x(z)^{\frac{\sigma-1}{\sigma}}, \tag{14}$$

$$w(z) = \beta \left(\frac{\sigma-1}{\sigma}\right)^2 \frac{1}{L(z)} x(z)^{\frac{\sigma-1}{\sigma}} \tag{15}$$

$$(1-\theta) \left(\frac{\sigma-1}{\sigma}\right)^2 \frac{\mathrm{d}S(z)}{\mathrm{d}z} \frac{1}{S(z)} x(z)^{\frac{\sigma-1}{\sigma}} = \frac{\mathrm{d}w(z)}{\mathrm{d}z} [R(z) + L(z)] + \frac{\mathrm{d}r(z)}{\mathrm{d}z}.$$

The first two expressions are standard. The last one means that, by moving away from the center $z = 0$, a firm incurs a decrease in the benefit generated by spillovers, which is exactly compensated by a decrease in wage and land rent. This condition is the counterpart of the Alonso-Muth equation obtained in the monocentric city model of urban economics (Fujita, 1989).

We can combine these three conditions to obtain the following equilibrium conditions:

$$\frac{R(z)}{L(z)} = \frac{\theta}{\beta}, \tag{16}$$

$$w(z) = \beta \left(\frac{\sigma-1}{\sigma}\right)^2 \frac{1}{L(z)} x(z)^{\frac{\sigma-1}{\sigma}}, \tag{17}$$

$$\frac{\mathrm{d}r(z)}{\mathrm{d}z} = \frac{L(z)}{\beta} \left[(1-\theta) \frac{w(z)}{S(z)} \frac{\mathrm{d}S(z)}{\mathrm{d}z} - (\theta + \beta) \frac{\mathrm{d}w(z)}{\mathrm{d}z}\right]. \tag{18}$$

The first condition means that the research-production labor ratio is equal to the ratio of their output elasticities, while the second states that the wage is proportional to the output per capita of a variety. The third condition implies that the land rent gradient is flatter when the spillover S is stronger because the benefit earned from clustering is higher. We acknowledge that having a constant fraction of workers employed in research vs. production, which does not depend on the city structure, is restrictive. However, this vastly simplifies the analytical analysis of the model.

It remains to show that the first-order conditions are also sufficient. We show in Appendix that firms' profit functions are strictly concave if and only if the inequality

$$\frac{\sigma}{\sigma-1} > \theta + \beta \tag{19}$$

holds. Estimations of the elasticity of substitution σ among inputs is 4.7 on average (Peter and Ruane, 2020), while the elasticity of production θ with respect to R&D is about 0.12 (Hall *et al.*, 2010). Since the land share is approximately 0.06 for manufacturing (Caselli and Coleman, 2001) and 0.15 for services (Brinkman *et al.*, 2015), we may safely conclude that the empirical evidence backs up the inequality $\sigma/(\sigma-1) > \theta+\beta$. In what follows, we assume that (19) holds true.

Using (14)-(15), the profit earned by a firm located at z is given by

$$\pi(z) = \left(\frac{\sigma}{\sigma-1} - \theta - \beta\right)\frac{L(z)w(z)}{\beta} - r(z).$$

Therefore, positive profits requires (19) to be satisfied. As a result, when (19) does not hold, there is no science park.

In equilibrium, intermediate firms earn the same profits. Therefore, the maximum bid that a firm can offer to set up at z, denoted by $r^F(z)$, is obtained from the zero-profit condition $\pi(z) = 0$:

$$r^F(z) = \left(\frac{\sigma}{\sigma-1} - \theta - \beta\right)\frac{L(z)w(z)}{\beta}. \tag{20}$$

This defines the bid rent by an intermediate firm at production site z. Thus, the bid rent by intermediate firms is positive if and only if (19) is met.

Differentiating (20) with respect to z and using the envelop theorem yield

$$\frac{\mathrm{d}r^F(z)}{\mathrm{d}z} = \left(\frac{\sigma}{\sigma-1} - \theta - \beta\right)\frac{L(z)}{\beta}\frac{\mathrm{d}w(z)}{\mathrm{d}z}.$$

Plugging (18) in this expression, we obtain the following differential equation in w:

$$\frac{\mathrm{d}w(z)}{\mathrm{d}z} = \frac{(1-\theta)(\sigma-1)}{\sigma}\frac{w(z)}{S(z)}\frac{\mathrm{d}S(z)}{\mathrm{d}z}.$$

Solving this differential equation yields

$$w(z) = C \cdot [S(z)]^{\frac{(1-\theta)(\sigma-1)}{\sigma}}, \tag{21}$$

where $C > 0$ is the constant of integration. Since $S(z)$ is strictly decreasing and strictly concave in z and $(1-\theta)(\sigma-1)/\sigma < 1$, *the equilibrium wage schedule is strictly decreasing and strictly concave in* z. In other words, the wage falls at a decreasing rate as the distance to the center of the cluster increases.

Plugging (1) into (17) leads to

$$\beta\left(\frac{\sigma-1}{\sigma}\right)^2 \frac{1}{L(z)}\left[R(z)^\theta \cdot (\bar{R}S(z))^{1-\theta} \cdot L(z)^\beta\right]^{\frac{\sigma-1}{\sigma}} = w(z).$$

Using (16) and (21), we obtain

$$\beta\left(\frac{\sigma-1}{\sigma}\right)^2 \frac{1}{L(z)}\left[\left(\frac{\theta}{\beta}\right)^\theta L(z)^\theta \cdot (\bar{R}S(z))^{1-\theta} \cdot L(z)^\beta\right]^{\frac{\sigma-1}{\sigma}} = C \cdot [S(z)]^{\frac{(1-\theta)(\sigma-1)}{\sigma}},$$

which, after simplifications, yields the equilibrium number of production workers hired by a firm located at z:

$$L(z) = \frac{\left[C \cdot \beta\left(\frac{\sigma-1}{\sigma}\right)^2\right]^{\frac{\sigma}{\beta(\sigma-1)-1}}}{\left(\frac{\theta}{\beta}N^{1-\theta}\right)^{\frac{\sigma-1}{\beta(\sigma-1)-1}}} \equiv L^*(N), \tag{22}$$

which is constant and hence the same across space. It then follows from (16) that the equilibrium mass of R&D workers $R(z) = \theta L^*(N)/\beta$ is also constant for all $z \in Z^F$. Therefore, *intermediate firms hire the same number of production workers and the same number of researchers regardless of their location within the cluster.*

We may rewrite (20) as follows:

$$r^F(z) = \left(\frac{\sigma}{\sigma-1} - \theta - \beta\right)\frac{L^*(N)}{\beta}w(z), \tag{23}$$

which implies that the bid rent of an intermediate firm at z is proportional to the wage that prevails at this location. Furthermore, since $w(z)$ is concave in z, (23) also implies that *firms' bid rent function is strictly decreasing and strictly concave in* z. More specifically, this function is given by the following expression:

$$r^F(z) = \left(\frac{\sigma}{\sigma-1} - \theta - \beta\right)\frac{L^*(N)}{\beta}C\,[S(z)]^{\frac{(1-\theta)(\sigma-1)}{\sigma}}.$$

Using (9), it follows from $M = \phi N$, $\bar{L} = NL^*$, and $\bar{R} = NR^* = (\theta/\beta)NL^*$ that the equilibrium mass of intermediate firms solves the equation:

$$H = \phi N + \frac{\beta+\theta}{\beta}L^*(N)N,$$

or,

$$L^*(N) = \frac{\beta}{\beta+\theta}\left(\frac{H}{N} - \phi\right) \tag{24}$$

while (16) implies

$$R^*(N) \equiv \frac{\theta}{\theta+\beta}\left(\frac{H}{N} - \phi\right). \tag{25}$$

Thus, the higher the elasticity of a firm's TFP with respect to its own R&D investment, the higher the number of researchers employed by this firms. To put it differently, as the spatial externality matters less ($\theta \uparrow$), each firm invests more in R&D. Note also that N is bounded above by H/ϕ because each firm must earn sufficiently high operating profits to cover the land rent.

Finally, using (1) and (2), it is readily verified that the equilibrium output of a firm located at z is equal to

$$x^*(z) = \frac{\theta}{\beta} \cdot [NS(z)]^{1-\theta} \cdot [L^*(N)]^{1+\beta}.$$

Therefore, *firms' size decreases with the distance to the city center.* The mass of firms has two conflicting effects. It, on the one hand, reduces employment at each firm but, on the other hand, raises the extent of spatial externality. Substituting (24) into this expression, it is readily verified that the employment effect dominates and hence the equilibrium size of a firm decreases with the mass of firms unambiguously.

3.3 Workers

We first determine the equilibrium mapping J from Z to Z that associates a (potential) job site $J(y) = z$ with a (potential) residential location y. This mapping describes the commuting pattern of workers. More specifically, a worker residing at y works at the location $J(y) = z$ that maximizes her net income:

$$w[J(y)] - t|y - J(y)| = \max_{z \in Z}\left[w(z) - t|y - z|\right], \qquad y \in Z.$$

Solving workers' program shows that the maximum bid a worker can offer to reside at location y is given by

$$r^W(y) = \max_{z}\left\{w[J(y)] - t|y - J(y)| - I(y, J(y)) \mid I(y, J(y)) = I_0\right\}. \tag{26}$$

This therefore defines the bid rent by a worker residing at location y.

The following result is intuitively obvious: in equilibrium, cross-commuting does not occur. Indeed, if two groups of workers cross-commute, any worker belonging to any of these groups would strictly increase her net income by choosing a job site in the area where the other group works. In other words, $J(y)$ increases in y. More specifically, we assume that the commuting function $J(y)$ is given by

$$z = J(y) = \frac{N}{H}(y - N/2), \qquad y \in [N/2, (H + N)/2]$$

so that workers living at $y = N/2$ work at $z = 0$, while those at $y = (H + N)/2$ work at $z = N/2$. Hence, a worker living in the residential area $[N/2, (H + N)/2]$ is assigned to a unique location belonging to $[0, N/2]$ with y and $J(y)$ varying in the same direction.

Combining (7) and (8) with (26), we obtain

$$r^W(y) = w(z) - t|y - J(y)| - I_0, \tag{27}$$

which means that *workers' bid rent functions are linear and downward slopping in distance.*

4 The science park

We determine the conditions for the spatial equilibrium to be a science park in two steps. In the first one, given N, we identify the conditions for a science park to emerge. In the second step, we determine the mass of intermediate firms. To produce clear-cut comparative results, we focus on symmetric firm distributions around the cluster center.

The equilibrium land rent $r^*(z)$ is the upper envelope of the two bid rent functions $r^F(z)$ and $r^W(z)$. In other words, whenever a firm or a worker locates at z, its bid rent must be equal to the equilibrium land rent:

$$\begin{aligned} r^*(z) &= \max\left\{r^F(z), r^W(z), 1\right\} \\ r^*(z) &= \begin{cases} r^F(z) & \text{if} \quad h^F(z) > 0 \\ r^W(z) & \text{if} \quad h^W(z) > 0 \end{cases} \\ r^*\left(-(N + H)/2\right) &= r^*((N + H)/2) = 1, \end{aligned}$$

where the bid rents $r^W(z)$ and $r^F(z)$ are given by (27) and (23), respectively. Since both $r^W(z)$ and $r^F(z)$ decrease with z, the equilibrium land rent also decreases as the distance to the center rises.

A *spatial equilibrium* is defined by the quantity vector $\{L^*, R^*, x^*(z), N^*\}$ and the price vector $\{p^*(z), w^*(z), r^*(z)\}$ for $z \in Z$ such that the following conditions are satisfied:

(i) profits are zero in the final and intermediate sectors;

(ii) land and labor markets clear;

(iii) the location sets of intermediate firms and workers are $Z^F = [-N/2, N/2]$ and $Z^W = [-(H+N)/2, -N/2] \cup [N/2, (H+N)/2]$;

(iv) market clearing for intermediate goods pins down the mass of intermediate firms;

(v) population constraint:$\int_{Z^W} h^W(z)\mathrm{d}z = H$.

The Walras Law implies that the final good market clears.

We have seen that the workers' bid rent schedule is linear and downward sloping while the firms' bid rent schedule is strictly decreasing and concave in z. In this case, the following two conditions are necessary and sufficient for a science park to be sustained as a spatial equilibrium:

(a) firms' and workers' bid rent schedules intersect at $z = N^*/2$;

(b) firms outbid workers at $z = 0$.

Indeed, condition (a) is necessary and sufficient to guarantee that workers outbid firms outside the science park, while condition (b) means that firms outbid workers within the park. It remains to check what conditions (a) and (b) are for a science park to emerge as an equilibrium outcome (see Figure 1).

Insert Figure 1 about here

4.1 Existence

We begin by determining the value of the constant of integration by equalizing firms' and workers' bit rents at $N/2$:

$$r^F(N/2) = \left(\frac{\sigma}{\sigma-1} - \theta - \beta\right)\frac{L^*(N)}{\beta}w(N/2) = 1 + \frac{tH}{2} = r^W(N/2). \tag{28}$$

Plugging (21) evaluated at $z = N/2$ into (28), we obtain:

$$\left(\frac{\sigma}{\sigma-1} - \theta - \beta\right)\frac{CL^*(N)}{\beta}\left(\frac{1-\mathrm{e}^{-\gamma N}}{\gamma}\right)^{\frac{(1-\theta)(\sigma-1)}{\sigma}} = 1 + \frac{tH}{2}, \tag{29}$$

which pins down the unique value of $C(N)$ for (28) to hold.

We next determine the condition for

$$r^F(0) > r^W(0) = 1 + t(N+H)/2. \tag{30}$$

to hold. This condition states that intermediate firms outbid workers toward the center of the high-tech city – a necessary condition for intermediate firms to cluster within our spatial framework. Since the firms' bid rent at $z = 0$ is given by

$$r^F(0) = \left(\frac{\sigma}{\sigma - 1} - \theta - \beta\right) \frac{L^*(N)}{\beta} w(0),$$

with

$$w(0) = C(N) \left(2\frac{1 - \mathrm{e}^{-\gamma N/2}}{\gamma}\right)^{\frac{(1-\theta)(\sigma-1)}{\sigma}}, \tag{31}$$

we obtain:

$$r^F(0) = \left(\frac{\sigma}{\sigma - 1} - \theta - \beta\right) \frac{C(N)L^*(N)}{\beta} \left(2\frac{1 - \mathrm{e}^{-\gamma N/2}}{\gamma}\right)^{\frac{(1-\theta)(\sigma-1)}{\sigma}}.$$

Then, we use (29) to replace $C(N)L^*(N)$ in the above equation to obtain the value of the firms' bid rent at $z = 0$:

$$r^F(0) = \left(1 + \frac{tH}{2}\right) \left(2\frac{1 - \mathrm{e}^{-\gamma N/2}}{1 - \mathrm{e}^{-\gamma N}}\right)^{\frac{(1-\theta)(\sigma-1)}{\sigma}}.$$

Using this expression, (30) may be rewritten as follows:

$$\left(1 + \frac{tH}{2}\right) \left(2\frac{1 - \mathrm{e}^{-\gamma N/2}}{1 - \mathrm{e}^{-\gamma N}}\right)^{\frac{(1-\theta)(\sigma-1)}{\sigma}} > 1 + t\frac{N+H}{2},$$

which is equivalent to

$$\left(2\frac{1 - \mathrm{e}^{-\gamma N/2}}{1 - \mathrm{e}^{-\gamma N}}\right)^{\frac{(1-\theta)(\sigma-1)}{\sigma}} > \frac{2 + t(H+N)}{2 + tH}. \tag{32}$$

The left-hand side of (32) is independent of t and larger than 1 for all $N > 0$, while the right-hand side is increasing and equal to 1 at $t = 0$. Therefore, there exists a unique solution in t for (32) to hold in equality, which we denote $T(N)$.[3]

[3] Proposition 1 is in accordance with Ogawa and Fujita (1980) who show in a different setting that a monocentric city emerges when commuting costs are sufficiently small.

Proposition 1. *For any given mass N of intermediate firms, a science park is a spatial equilibrium if and only if $t < T(N)$.*

This proposition has an important policy implication: commuting must be fairly inexpensive for a science park to emerge. This highlights the need for modern and efficient transportation and communication infrastructures in a science park. As empirical evidence suggests that knowledge spillovers are very localized (see, e.g., Arzaghi and Henderson, 2008, Lychagin *et al.*, 2016 and Helmers, 2019), it is worth studying how $T(N)$ varies with γ. Since the left-hand side of (32) shifts upward when γ rises, the value of $T(N)$ increases, which makes it easier for (32) to be satisfied.

Moreover, since the right-hand side of (32) shifts downward when H increases, the value of $T(N)$ increases as well. In sum, we have:

Proposition 2. *For any given mass N of intermediate firms, very localized spillovers (high γ) or a bigger pool of skilled workers (high H) fosters the making of a science park.*

4.2 The size of a science park

We now focus on the determination of the equilibrium number of intermediate firms that sustains a science park.

Plugging (31) into (12), we obtain

$$x(N/2)^{\frac{\sigma-1}{\sigma}} = \sigma\phi C(N)\left(2\frac{1-\mathrm{e}^{-\gamma N/2}}{\gamma}\right)^{\frac{(1-\theta)(\sigma-1)}{\sigma}},$$

or,

$$C(N) = \frac{x(N/2)^{\frac{\sigma-1}{\sigma}}}{\sigma\phi\left(2\frac{1-\mathrm{e}^{-\gamma N/2}}{\gamma}\right)^{\frac{(1-\theta)(\sigma-1)}{\sigma}}}.$$

Substituting $C(N)$ into (22) yields

$$L^*(N)^{\frac{\beta(\sigma-1)-1}{\sigma}} = \beta\left(\frac{\sigma-1}{\sigma}\right)^2 \frac{x(N/2)^{\frac{\sigma-1}{\sigma}}}{\sigma\phi\left(2\frac{1-\mathrm{e}^{-\gamma N/2}}{\gamma}\right)^{\frac{(1-\theta)(\sigma-1)}{\sigma}}}\frac{1}{\left(\frac{\theta}{\beta}N^{1-\theta}\right)^{\frac{\sigma-1}{\sigma}}}. \tag{33}$$

Using (1), we obtain the equilibrium output:

$$x^*(N/2) = \frac{\theta}{\beta}L^*(N)^{1+\beta}N^{1-\theta}S(N/2)^{1-\theta} = \frac{\theta}{\beta}L^*(N)^{1+\beta}N^{1-\theta}\left[\frac{1}{\gamma}\left(1-\mathrm{e}^{-\gamma N}\right)\right]^{1-\theta}, \tag{34}$$

because the marginal variety N is produced at the edge of the cluster.

Combining (33) and (34) yields

$$L^*(N)^{\frac{\beta(\sigma-1)-1}{\sigma}} = \beta\left(\frac{\sigma-1}{\sigma}\right)^2 \cdot \frac{\left\{\frac{\theta}{\beta}N^{1-\theta}L^*(N)^{1+\beta}\left[\frac{1}{\gamma}(1-\mathrm{e}^{-\gamma N})\right]^{1-\theta}\right\}^{\frac{\sigma-1}{\sigma}}}{\sigma\phi\left[2\left(1-\mathrm{e}^{-\gamma N/2}\right)\right]^{\frac{(1-\theta)(\sigma-1)}{\sigma}}} \cdot \frac{\gamma^{\frac{(1-\theta)(\sigma-1)}{\sigma}}}{\left(\frac{\theta}{\beta}N^{1-\theta}\right)^{\frac{\sigma-1}{\sigma}}},$$

or, after simplifications,

$$L^*(N) = \frac{\sigma\phi}{\beta}\left(\frac{\sigma}{\sigma-1}\right)^2\left[\frac{2\left(1-\mathrm{e}^{-\gamma N/2}\right)}{1-\mathrm{e}^{-\gamma N}}\right]^{\frac{(1-\theta)(\sigma-1)}{\sigma}}. \tag{35}$$

Equalizing (24) and (35) leads to

$$F(N) \equiv \frac{\sigma\phi}{\beta}\left(\frac{\sigma}{\sigma-1}\right)^2\left(2\frac{1-\mathrm{e}^{-\gamma N/2}}{1-\mathrm{e}^{-\gamma N}}\right)^{\frac{(1-\theta)(\sigma-1)}{\sigma}} = \frac{\beta}{\beta+\theta}\left(\frac{H}{N}-\phi\right) \equiv G(N). \tag{36}$$

The function $F(N)$ is increasing in N with $F(0) > 0$, while $G(N)$ decreases in N with $G(0) \to \infty$ and $\lim_{N\to\infty} G(N) < 0$. Therefore, (36) has a unique solution, which yields the equilibrium mass of firms N^* in the intermediate sector.

Summarizing yields the following proposition.

Proposition 3. *There exists a unique mass of intermediate firms N^*such that a science park is a spatial equilibrium when $t < T(N^*)$.*

Since $F(N)-G(N)$ increases with N, γ and ϕ but decreases with H, we have the following proposition.

Proposition 4. *In spatial equilibrium, a lower labor requirement for designers ($\phi \downarrow$), a weaker distance-decay effect ($\gamma \downarrow$), or a bigger skilled labor pool ($H \uparrow$) leads to a higher mass of intermediate firms and a larger science park.*

Intuitively, abundant availability of skilled workers or lower coordination cost enables high-tech production with a longer production line. Moreover, a weaker distance-decay effect counters the necessary dispersion of intermediate firms as a result of required land usage and the rising wage cost to compensate longer commuting by workers, thereby permitting a larger science park to form in equilibrium.

How would the likelihood of science park formation change in response to these key parameters? Recall that the commuting cutoff $T(N)$ is pinned down by (32) in equality:

$$\left(2\frac{1-\mathrm{e}^{-\gamma N/2}}{1-\mathrm{e}^{-\gamma N}}\right)^{(1-\theta)\frac{\sigma-1}{\sigma}} = \frac{2+T(N)(H+N)}{2+T(N)H},$$

while the equilibrium mass of firms N^* is determined by (36). Define $t^* \equiv T(N^*)$. Plugging (36) into the above expression yields a relationship between N^* and t^*:

$$\left(\frac{\sigma-1}{\sigma}\right)^2 \frac{\beta^2}{\sigma\phi(\beta+\theta)}\left(\frac{H}{N^*}-\phi\right) = \frac{2+t^*(H+N^*)}{2+t^*H}. \tag{37}$$

Totally differentiating this expression and solving for $\mathrm{d}t^*/\mathrm{d}N^*$, we obtain:

$$\frac{\mathrm{d}t^*}{\mathrm{d}N^*} = -\frac{(2+t^*H)^2}{2N^*}\left[\left(\frac{\sigma-1}{\sigma}\right)^2 \frac{\beta^2}{\sigma\phi(\beta+\theta)}\frac{H}{(N^*)^2} + \frac{t^*}{2+t^*H}\right] < 0.$$

In other words, the commuting cutoff t^* evaluated at the equilibrium mass of firms $N^*$is decreasing in the equilibrium mass of intermediate firms. Note that labor requirement for designers does not affect the commuting cutoff directly. Thus, Proposition 4 implies that a lower coordination cost would raise the mass of intermediate firms and reduce the likelihood for a science park to form. This is interesting. Let us consider an economy with continual improvements in infrastructure and communication technology that lowers the coordination cost captured by ϕ. At an initial equilibrium (N^*, t^*), the condition for the formation of the science park $t < t^*$ is met. With continual reduction in ϕ, the size of the science park continues to grow until N^{**} at which $t = T(N^{**})$ holds, after which it ceases to grow even if ϕ continues to fall. This is the stage at which a single science park will be decentralized into multiple ones. This fragmentation of science parks may serve to explain the evolution of the Silicon Valley, which began with Palo Alto Industrial Park in 1951, expanded to Mountain View, then to Sunnyvale, Santa Clara and, eventually, San Jose and its adjacent municipals (Saxenian 1994, pp. 29-30).

To sum up, we have the following proposition.

Proposition 5. *In equilibrium, continual improvements in infrastructure and communication technology that lowers the coordination cost ($\phi \downarrow$) may result in fragmentation of science parks.*

Recall from Proposition 4 that a weaker distance-decay effect ($\gamma \downarrow$) makes science park larger ($N^* \uparrow$). Rearranging (37) yields

$$\frac{1}{N^*}\left[\left(\frac{\sigma-1}{\sigma}\right)^2 \frac{\beta^2}{\sigma\phi(\beta+\theta)}\left(\frac{H}{N^*}-\phi\right) - 1\right] = \frac{t^*}{2+t^*H},$$

which is not directly affected by γ. Since the left-hand side of this expression is a decreasing function of N^* while the right-hand side increases with t^*, the latter decreases with a weaker distance-decay effect ($\gamma \downarrow$). In other words, *more localized spillovers make science park more likely to form, but Proposition 4 implies that the equilibrium size of the science park is smaller.*

By contrast, the effect of a larger labor pool is a priori ambiguous. Indeed, for a given mass N of intermediate firms, Proposition 2 implies that a higher value of H raises the commuting cutoff t^*. However, Proposition 4 implies that a bigger labor pool also induces a larger equilibrium mass of intermediate firms. This in turn reduces the commuting cutoff. Yet, we show in the Appendix that the cutoff t^* may decrease with the size of the labor pool when t^* takes intermediate values. Specifically, when the labor pool is sufficiently large, there exist two commuting rates $0 < t_1 < t_2$ such that $\mathrm{d}t^*/\mathrm{d}H < 0$ holds over (t_1, t_2). Thus, when $t^* \in (t_1, t_2)$, a further increase in the labor pool leads to a lower cutoff $t^{**} < t^*$. Should the new cutoff t^{**} fall below the current commuting cost rate t, the city would turn out to host too many workers to sustain its science park.

5 Counterfactual: The flat city

In this section, we consider the extreme case of a fully dispersed configuration (denoted with subscript D), which features workers and intermediate firms that cohabit at each location. Since the total demand for land is $N + H$, the worker density is equal to $h_D^W = H/(N + H)$, while the firm density is $h_D^F = N/(N + H)$. Since firms and workers are uniformly distributed across the city, we refer to such a configuration as a *flat city.*

To ensure the existence of a flat city, the following two conditions must be met: (i) firms and workers have identical bid rents; (2) a worker's residence and workplace are the same, i.e., $J(y) = y$. It can be shown that the commuting rate t must be sufficiently large for these two conditions to be satisfied. This is obvious because with sufficiently high commuting cost, it would be impossible for firms to outbid workers after paying sufficiently high wage to compensate commuting workers. Thus, in what follows, we do not investigate the equilibrium conditions that t must satisfy the flat city to be a spatial equilibrium. Instead, we undertake a counterfactual in which the parameters of the economy are the same as in a science park but where their spatial arrangement, perhaps inherited from the past, is given by a flat city. We then compare the equilibrium wage schedules, land rents and welfare in a science park and flat city. Since all the equilibrium conditions of Section 3 remain valid in the case of a flat city, we index the corresponding magnitudes by D and proceed exactly as in Section 4 to characterize the equilibrium mass of firms in a flat city.

In a flat city, the distance-decay effect is as follows:

$$S_D(z) = \frac{1}{\gamma}\frac{N}{N+H}\left[2 - \mathrm{e}^{-\gamma\frac{N+H}{2}}(\mathrm{e}^{-\gamma z} + \mathrm{e}^{\gamma z})\right] < S(z). \tag{38}$$

In other words, for the same research pool, *the spatial externality is stronger in a science park than in a flat city.*

5.1 The size of a flat city

First, at the city edge $(N+H)/2$, firms' and workers' bid rents are equal:

$$r_D^F((N+H)/2) = \left(\frac{\sigma}{\sigma-1} - \theta - \beta\right)\frac{L_D^*(N)w_D((N+H)/2)}{\beta} = r_D^H((N+H)/2) = 1.$$

Plugging the equilibrium wage (21), we obtain:

$$\left(\frac{\sigma}{\sigma-1} - \theta - \beta\right)C_D L_D^*(N)\left[S_D\left(\frac{N+H}{2}\right)\right]^{\frac{(1-\theta)(\sigma-1)}{\sigma}} = \beta.$$

Second, combining (12) and (21) yields the constant of integration in the case of a flat city:

$$C_D(N) = \frac{x_D(N/2)^{\frac{\sigma-1}{\sigma}}}{\sigma\phi\left[S_D(0)\right]^{(1-\theta)\frac{\sigma-1}{\sigma}}}.$$

Plugging $C_D(N)$ into (22) gives

$$L_D^*(N)^{\frac{\beta(\sigma-1)-1}{\sigma}} = \beta\left(\frac{\sigma-1}{\sigma}\right)^2\frac{x_D(N/2)^{\frac{\sigma-1}{\sigma}}}{\sigma\phi S_D(0)^{\frac{(1-\theta)(\sigma-1)}{\sigma}}}\frac{1}{\left(\frac{\theta}{\beta}N^{1-\theta}\right)^{\frac{\sigma-1}{\sigma}}}. \tag{39}$$

Using (1), we obtain:

$$x_D(N/2) = \frac{\theta}{\beta}N^{1-\theta}(L_D^*(N))^{1+\beta}\left[S_D((N+H)/2)\right]^{1-\theta}. \tag{40}$$

Combining (39) and (40) yields:

$$L_D^*(N)^{\frac{\beta(\sigma-1)-1}{\sigma}} = \beta\left(\frac{\sigma-1}{\sigma}\right)^2\frac{\left[\frac{\theta}{\beta}N_D^{1-\theta}\cdot(L_D^*(N))^{1+\beta}\cdot S_D((N+H)/2)^{1-\theta}\right]^{\frac{\sigma-1}{\sigma}}}{\sigma\phi S_D(0)^{\frac{(1-\theta)(\sigma-1)}{\sigma}}}\frac{1}{\left(\frac{\theta}{\beta}N^{1-\theta}\right)^{\frac{\sigma-1}{\sigma}}}.$$

Evaluating (38) at $z=0$ and $z=(N+H)/2$ and simplifying leads to

$$L_D(z) = \frac{\sigma\phi}{\beta}\left(\frac{\sigma}{\sigma-1}\right)^2\left(2\frac{1-\mathrm{e}^{-\gamma\frac{N+H}{2}}}{1-\mathrm{e}^{-\gamma(N+H)}}\right)^{(1-\theta)\frac{\sigma-1}{\sigma}} \equiv L_D^*(N), \tag{41}$$

which is independent of z, like in the case of a science park. The same holds for $R_D^*(N)$.

Equalizing (41) and (24) leads to the following equation in N:

$$\frac{\sigma\phi}{\beta}\left(\frac{\sigma}{\sigma-1}\right)^2\left(2\frac{1-\mathrm{e}^{-\gamma\frac{N+H}{2}}}{1-\mathrm{e}^{-\gamma(N+H)}}\right)^{\frac{(1-\theta)(\sigma-1)}{\sigma}}=\frac{\beta}{\beta+\theta}\left(\frac{H}{N}-\phi\right). \tag{42}$$

By similar argument above, this equation also has a unique solution, which is denoted as N_D. Since the right-hand side of (36) and (42) are the same while the left-hand side of (42) lies above (36), we may conclude:

Proposition 6. *In spatial equilibrium, there are more intermediate firms in a science park than in a flat city, i.e.,* $N^* > N_D$.

The above results show that, in our setting, the efficiency of the intermediate and final sectors is endogenized through the R&D activities undertaken by intermediate firms and the size of the researcher pool, which both vary with the spatial configuration adopted by firms and workers.

5.2 Is a science park more efficient than a flat city?

It is plausible that designing a production line is more costly in a flat city than in an agglomerated one because dispersion gives rise to higher coordination costs. We capture this idea by assuming that more coordinating workers are required in a flat city, i.e., $\phi < \phi_D$. How does this change in ϕ affect the structure of employment in the flat city?

Using (24), the total mass of workers employed in producing the intermediate goods is given by

$$\bar{L} = NL^*(N) = \frac{\beta}{\beta+\theta}\left(H-\phi N\right). \tag{43}$$

Clearly, how $\bar{L}$ varies with ϕ depends on whether the elasticity of the equilibrium mass of firms with respect to ϕ is larger or smaller than -1. Total differentiation of (36) gives the elasticity of N with respect to ϕ:

$$\varepsilon(N) \equiv \frac{\phi}{N}\frac{\mathrm{d}N}{\mathrm{d}\phi} = -\frac{\frac{H}{N}}{\frac{H}{N}+(1-\theta)\gamma\frac{\sigma-1}{\sigma}\left(\frac{1}{2}\frac{\mathrm{e}^{-\gamma\frac{N}{2}}}{1-\mathrm{e}^{-\gamma\frac{N}{2}}}-\frac{\mathrm{e}^{-\gamma N}}{1-\mathrm{e}^{-\gamma N}}\right)\left(\frac{H}{N}-\phi\right)} > -1.$$

From (43), $\bar{L}$ is thus decreasing in ϕ. As a consequence, it follows from (9), (24) and (25) that $\bar{L}^* > \bar{L}_D^*$, $\bar{R}^* > \bar{R}_D^*$ and $M^* < M_D$ when $\phi < \phi_D$. In other words, *a science park hosts more researchers and production workers than a flat city.* By implication, the final sector is more productive when a science park is formed because more intermediate inputs are available while more workers are involved in production. To put it differently, the final sector benefits from a finer division of labor when a science park exists. This may explain why it is rewarding for a city to host a science park, as suggested by the empirical evidence provided by Delgado *et al.* (2012).

Note that the productivity of the final sector is entirely channelized through employment of researchers and designers, as well as by the total size of the researcher pool in the science park. Moreover, these two effects are reinforced by the magnitude of the spatial spillover effect, which takes on its highest values when firms cluster in a single science park. These results may serve to explain why the extent of the proximity effect may vary by location or by industry (see the survey by Carlino and Kerr, 2015, Section 4.3).

In addition, it follows from (25) that each firm hires fewer researchers in a science park. Hence, even though each firm employs fewer researchers, a science park involves a bigger pool of researchers and undertake more R&D through a larger mass of firms. Since it accommodates more intermediate firms, the size of the city that hosts a science park is also larger than that of a city without a science park.

We summarize the aforementioned results in the following proposition.

Proposition 7. *In spatial equilibrium, city with a science park hosts more researchers and production workers, but fewer designers, than a flat city. Furthermore, the intermediate sector involves more firms while the final sector is more productive in a science park than in a flat city.*

5.3 Welfare, wages and land rent

Proposition 1 implies that firms outbid workers over Z^F in a science park, whereas workers' and firms' bid rents are identical and linear in a flat city. Since the land rent at the city limit is equal to 1, *the land rent is higher in a science park than in a flat city* over Z^F while it is the same over Z^W. This is because the higher benefits generated by the spatial externality in a science park ($S(z) > S_D(z)$) are partially capitalized in the land rent.

Likewise, since $L^*(z)$ is smaller in a science park than in a flat city, it follows from (23) that wages are higher in the former than in the latter over Z^F.[4] Here too, wages capitalize the higher productivity triggered by the spatial externality in a science park. Furthermore,

[4] We cannot compare wages over $(-(N+H)/2, -N/2) \cup ((N+H)/2, N/2)$ because it is residential area in a science park.

using (23) again, as well as $L^* < L_D^*$ shows that *the wage gap between the science park and the flat city is wider than the difference in land rents* over Z^F. In other words, everything else being equal, the workers benefit more from the clustering of intermediate firms than the land owners. To conclude, in a science park workers earn higher wages but bear positive commuting costs. The difference in welfare is thus a priori ambiguous. To this end, we undertake a welfare comparison of the two configurations.

Using (7) shows that, in a science park, the indirect utility level of a worker who works at $N^*/2$ and lives at $(N^* + H)/2$ is given by

$$I\left(\frac{N^* + H}{2}\right) = w(N^*/2) - tH/2 - 1.$$

Plugging the equilibrium wage (21) and the constant of integration (29) in this expression and simplifying leads to

$$I\left(\frac{N^* + H}{2}\right) = \left[\frac{\beta + \theta}{\left(\frac{\sigma}{\sigma-1} - \theta - \beta\right)\left(\frac{H}{N^*} - \phi\right)} - 1\right]\left(1 + \frac{tH}{2}\right). \tag{44}$$

In a flat city, a worker who works and lives at $(N^* + H)/2$ enjoys an indirect utility level given by

$$I_D\left(\frac{N_D + H}{2}\right) = w_D\left(\frac{N_D + H}{2}\right) - 1,$$

which is equivalent to

$$I_D\left(\frac{N_D + H}{2}\right) = \frac{\beta + \theta}{\left(\frac{\sigma}{\sigma-1} - \theta - \beta\right)\left(\frac{H}{N_D} - \phi\right)} - 1. \tag{45}$$

Since $N^* > N_D$, (44) and (45) imply

$$I\left(\frac{N^* + H}{2}\right) > I_D\left(\frac{N_D + H}{2}\right).$$

Since the indirect utility level is independent of the location z, welfare is higher in a science park, i.e., $I(z) > I_D(z)$ for any z. In other words, the finer division of labor in the final sector caused by the geographical concentration of firms leads to a higher utility level in the science park than in the flat city.

To sum up, we have the following proposition.

Proposition 8. *Wages and land rents are higher in a science park than in a flat city. Despite incurring higher commuting costs, workers are better off in a science park than in a flat city.*

This proposition also implies that, when the high-tech city is allowed to accommodate potential skilled workers from the ROW, the science park attracts more workers than the flat city. As a consequence, the former hosts a bigger population than the latter, which makes the science park even more productive.

6 Concluding remarks

In this paper, we have developed a spatial equilibrium model of a science park in the presence of positive knowledge spillovers between monopolistically competitive intermediate firms. We have shown that a science park is more likely to host a intermediate sector in which firms' TFP is mainly driven by the aggregate R&D expenditure. With this proviso, a science park is more likely to form under strongly localized knowledge spillovers, skilled labor abundance, and low commuting costs. We have also shown that, compared to a counterfactual flat city, a science park grants higher productivity to the production of the final good, hosts more intermediate firms, more researchers and more production workers, and generates greater worker welfare. Finally, we have illustrated why continual improvements in infrastructure and communication technology that lowers coordination costs may lead to eventual fragmentation of science parks.

Although we have confirmed the social desirability of science parks from the viewpoints of worker welfare, it is worth checking whether the typical science park promotion policies may work effectively. One of the most common instruments used by governments is to reduce firms' startup costs which can be translated into the reduction in the coordination cost for setting up the production line. Our analysis suggests that implementing such a policy need not achieve its goals. By contrast, subsidizing land may incentivize firms to cluster in a large science park. More specifically, with subsidy Δr, the equilibrium land rent becomes $r_j(z) = \max\left\{r_j^F(z) + \Delta r, r_j^W(z)\right\}$. This generates a discontinuity in firms' bid rents at the border between industrial and residential areas, thus enabling firms to outbid workers and to occupy more land within the inner area of the high-tech city. Having illustrated briefly the working of this land subsidy policy, we leave the full welfare analysis of this and other plausible policy instruments, by maintaining neutral government revenues, for future work.

We have considered a closed city model in which the total population is fixed. A promising step for future research is to determine the equilibrium population size of the science park by using an open city setting in which workers are free to migrate in and out while the utility level is exogenously given by the best option available in the ROW. In this way, firms' incentive to cluster will interact with workers' incentive to migrate, potentially leading to richer equilibrium outcomes. Another important extension is to dig further into the black box of spillovers by assuming with Davis and Dingel (2019) that face-to-face contacts across workers are costly and freely chosen, and to determine the condition for a science park to emerge in such a social environment. Equally important, like in Behrens *et al.* (2014), our setting should be extended to deal with an urban system that involves heterogeneous workers, as well as cities that host a science park and cities that do not. These are likely rewarding avenues for future research.

Appendix

This Appendix provides detailed proof of two technical properties.

Second-Order Condition. To show that firms' profit functions are strictly concave in (R, L), we compute the second derivatives of (13):

$$\frac{\partial^2 \pi}{\partial R^2(z)} = \theta\left(\theta\frac{\sigma-1}{\sigma}-1\right)\left(\frac{\sigma-1}{\sigma}\right)^2 \frac{x^{\frac{\sigma-1}{\sigma}}(z)}{R(z)^2} < 0,$$

$$\frac{\partial^2 \pi}{\partial L^2(z)} = \beta\left(\beta\frac{\sigma-1}{\sigma}-1\right)\left(\frac{\sigma-1}{\sigma}\right)^2 \frac{x^{\frac{\sigma-1}{\sigma}}(z)}{L(z)^2} < 0,$$

$$\frac{\partial^2 \pi}{\partial R(z)\partial L(z)} = \beta\theta\left(\frac{\sigma-1}{\sigma}\right)^3 \frac{x^{\frac{\sigma-1}{\sigma}}(z)}{L(z)R(z)}.$$

Since the Hessian matrix $H(z)$ of $\pi(z)$ is given by

$$H = \begin{pmatrix} \theta\left(\theta\frac{\sigma-1}{\sigma}-1\right)\left(\frac{\sigma-1}{\sigma}\right)^2 \frac{x^{\frac{\sigma-1}{\sigma}}(z)}{R(z)^2} & \beta\theta\left(\frac{\sigma-1}{\sigma}\right)^3 \frac{x^{\frac{\sigma-1}{\sigma}}(z)}{L(z)R(z)} \\ \beta\theta\left(\frac{\sigma-1}{\sigma}\right)^3 \frac{1}{L(i,z)R(i,z)} x_j^{\frac{\sigma-1}{\sigma}}(i,z) & \beta\left(\beta\frac{\sigma-1}{\sigma}-1\right)\left(\frac{\sigma-1}{\sigma}\right)^2 \frac{x^{\frac{\sigma-1}{\sigma}}(z)}{L(z)R(z)} \end{pmatrix}.$$

the second-order condition holds if and only if $|H(z)| > 0$, that is,

$$|H| = \theta\beta\left(\theta\frac{\sigma-1}{\sigma}-1\right)\left(\frac{\sigma-1}{\sigma}\right)^4 \frac{x^{2\frac{\sigma-1}{\sigma}}(z)}{L(z)^2 R(z)^2}\left(\beta\frac{\sigma-1}{\sigma}-1\right) - \left[\beta\theta\left(\frac{\sigma-1}{\sigma}\right)^3 \frac{x^{\frac{\sigma-1}{\sigma}}(z)}{L(z)R(z)}\right]^2,$$

or, after simplifications,

$$|H| = \beta\theta\left(\frac{\sigma-1}{\sigma}\right)^5\left(\frac{\sigma}{\sigma-1}-\theta-\beta\right)\frac{x_j^{2\frac{\sigma-1}{\sigma}}(i,z)}{R(i,z)^2 L(i,z)^2} > 0,$$

which is equivalent to (19). Q.E.D.

Equilibrium Effect of H on $T(N^*)$. Differentiating (36) and (37) with respect to H yields at N^*:

$$F'(N)N' = \frac{N - HN'}{N^2},$$

$$\left(\frac{\sigma-1}{\sigma}\right)^2 \frac{\beta^2}{(\beta+\theta)\sigma\phi}\frac{N-HN'}{N^2} = \frac{(t^{*\prime}N + t^*N')(2+t^*H) - t^*N(t^{*\prime}H + t^*)}{(2+t^*H)^2},$$

or, after simplifications,

$$N' = \frac{1}{NF'(N) + \frac{H}{N}},$$

$$\frac{2t^{*\prime}N}{(2+t^*H)^2}=\frac{Nt^{*2}}{(2+t^*H)^2}+\left(\frac{\sigma-1}{\sigma}\right)^2\frac{\beta^2}{(\beta+\theta)\sigma\phi}\frac{1}{N}-\left[\left(\frac{\sigma-1}{\sigma}\right)^2\frac{\beta^2}{(\beta+\theta)\sigma\phi}\frac{H}{N^2}+\frac{t^*}{(2+t^*H)}\right]N'.$$

Combining these two equations leads to

$$2t^{*\prime}N=Nt^{*2}+\left(\frac{\sigma-1}{\sigma}\right)^2\frac{\beta^2}{(\beta+\theta)\sigma\phi}\frac{(2+t^*H)^2}{N}-\left[\left(\frac{\sigma-1}{\sigma}\right)^2\frac{\beta^2}{(\beta+\theta)\sigma\phi}\frac{H}{N^2}+\frac{t^*}{2+t^*H}\right]\frac{(2+t^*H)^2}{NF'(N)+\frac{H}{N}}.$$

Simplifying, we obtain

$$2t^{*\prime}N\left(NF'(N)+\frac{H}{N}\right)=N^2t^{*2}F'(N)+\left(\frac{\sigma-1}{\sigma}\right)^2\frac{\beta^2(2+t^*H)^2}{(\beta+\theta)\sigma\phi}F'(N)-2t^*,$$

or, equivalently,

$$2\left(N^2F'(N)+H\right)t^{*\prime}=\Psi(t^*)\equiv F'(N)\left[N^2+H^2\left(\frac{\sigma-1}{\sigma}\right)^2\frac{\beta^2}{(\beta+\theta)\sigma\phi}\right]t^{*2}- \tag{A.1}$$

$$2\left[1-2H\left(\frac{\sigma-1}{\sigma}\right)^2\frac{\beta^2}{(\beta+\theta)\sigma\phi}F'(N)\right]t^*+4\left(\frac{\sigma-1}{\sigma}\right)^2\frac{\beta^2}{(\beta+\theta)\sigma\phi}F'(N).$$

Since $\Psi(t^*)$ is a quadratic function of t^*, it has at most two roots t_1 and t_2 with $t_1<t_2$. We now determine conditions for both roots are positive. Note $\Psi(t^*)$ is minimized at

$$\bar{t}=\frac{1}{F'(N)}\frac{1-2H\left(\frac{\sigma-1}{\sigma}\right)^2\frac{\beta^2}{(\beta+\theta)\sigma\phi}F'(N)}{N^2+H^2\left(\frac{\sigma-1}{\sigma}\right)^2\frac{\beta^2}{(\beta+\theta)\sigma\phi}}.$$

Since $\Psi(0)>0$ and $\Psi(\cdot)$ is convex, $0<t_1<t_2$ holds if $\bar{t}>0$ and $\Psi(\bar{t})<0$. Since $F'(N)>0$, the former holds if

$$F'(N)<\left(\frac{\sigma}{\sigma-1}\right)^2\frac{(\beta+\theta)\sigma\phi}{2H\beta^2}. \tag{A.2}$$

Plugging $\bar{t}$ in (A.1), we obtain after simplifications:

$$2\left[N^2+H^2\left(\frac{\sigma-1}{\sigma}\right)^2\frac{\beta^2}{(\beta+\theta)\sigma\phi}\right]t^{*\prime}(\bar{t})= \tag{A.3}$$

$$=4\left(\frac{\sigma-1}{\sigma}\right)^2\frac{\beta^2}{(\beta+\theta)\sigma\phi}-\frac{1}{F'(N)(N^2F'(N)+H)}.$$

(A.2) implies that the highest admissible value of $F'(N)$ is given by

$$F'(N)=\left(\frac{\sigma}{\sigma-1}\right)^2\frac{(\beta+\theta)\sigma\phi}{2H\beta^2}.$$

It then follows from (A.3) that $t^{*\prime}(\bar{t})<0$ when H is sufficiently large. By implication of (A.1), $\Psi(\bar{t})<0$ when H is large enough. Q.E.D.

References

[1] Aghion, P. and X. Jaravel (2015) Knowledge spillovers, innovation and growth. *Economic Journal* 125: 533-73.

[2] Arzaghi, M. and J.V. Henderson (2008) Networking off Madison Avenue. *Review of Economic Studies* 75: 1011-38.

[3] Audretsch, D. and M. Feldman (2004) Knowledge spillovers and the geography of innovation. In: J.V. Henderson and J.-F. Thisse (eds.) *Handbook of Urban and Regional Economics, Volume 4*. North-Holland, Amsterdam, 2713-39.

[4] Becker, G.S and K.M. Murphy (1992) The division of labor, coordination costs, and knowledge. *Quarterly Journal of Economics* 107: 1137-60.

[5] Behrens, K., G. Duranton, and F. Robert-Nicoud (2014) Productive cities: Sorting, selection and agglomeration. *Journal of Political Economy* 122: 507-53.

[6] Berliant, M., S.-K. Peng, and P. Wang (2002) Production externalities and urban configuration. *Journal of Economic Theory* 104: 275-303.

[7] Brinkman, J., Coen-Pirani, D., and H. Sieg (2015) Firm dynamics in an urban economy. *International Economic Review* 56: 1135-64.

[8] Buzard, K., G.A. Carlino, R.M. Hunt, J.K. Carr, and T.E. Smith (2017) The agglomeration of American R&D labs. *Journal of Urban Economics* 101: 14-26.

[9] Carlino, G.A. and W.R. Kerr (2015) Agglomeration and innovation. In: G. Duranton, J.V. Henderson and W. Strange (eds.) *Handbook of Regional and Urban Economics. Volume 5.* Amsterdam, Elsevier, 349-404.

[10] Caselli, F. and W.J. Coleman II (2001) The U.S. structural transformation and regional convergence: A reinterpretation. *Journal of Political Economy* 109: 584-616.

[11] Castells, M. and P.G. Hall (1994) *Technopoles of the World: The Making of Twenty-first-century Industrial Complexes*. London, Routledge.

[12] Chen, T.-J. (2008) The emergence of Hsinchu Science Park as an IT cluster. In: S. Yusuf, K. Nabeshima and S. Yamashita (eds.) *Growing Industrial Clusters in Asia: Serendipity and Science*. Washington, DC, The World Bank, 67-89.

[13] Chyi, Y. L., Y.M. Lai, and W.H. Liu (2012) Knowledge spillovers and firm performance in the high-technology industrial cluster. *Research Policy* 41: 556-64.

[14] Combes, P.-P. and L. Gobillon (2015) The empirics of agglomeration economies. In: G. Duranton, J.V. Henderson and W. Strange (eds.) *Handbook of Regional and Urban Economics. Volume 5.* Amsterdam, Elsevier, 247-348.

[15] Davis, D.R. and J. Dingel (2019) A spatial knowledge economy. *American Economic Review* 109: 153-70.

[16] de Palma, A., Y.Y. Papageorgiou, J.-F. Thisse, and P. Ushchev (2019) About the origin of cities. *Journal of Urban Economics* 111: 1-13.

[17] Delgado, M., M.E. Porter, and S. Stern (2014) Clusters, convergence, and economic performance. *Research Policy* 43: 1785-99.

[18] Desmet, K. and E. Rossi-Hansberg (2012) Innovation in space. *American Economic Review. Papers & Proceedings* 102: 447-52.

[19] Desmet, K. and E. Rossi-Hansberg (2014) Spatial development. *American Economic Review* 104: 1211-43.

[20] Duranton, G. and D. Puga (2004) Micro-foundations of urban increasing returns: Theory. In: J.V. Henderson and J.-F. Thisse (eds.) *Handbook of Urban and Regional Economics. Volume 4*. Amsterdam, North-Holland, 2063-117.

[21] Duranton, G., Ph. Martin, T. Mayer, and F. Mayneris (2010) *The Economics of Clusters*. Oxford, Oxford University Press.

[22] Fujita, M. (1989) *Urban Economic Theory*. Cambridge, Cambridge University Press.

[23] Fujita, M. and F. Ogawa (1982) Multiple equilibria and structural transition of non-monocentric urban configurations. *Regional Science and Urban Economics* 12: 161-96.

[24] Greenstone, M., R. Hornbeck, and E. Moretti (2010) Identifying agglomeration spillovers: Evidence from winners and losers of large plant openings. *Journal of Political Economics* 118: 536-98.

[25] Hall, B. J. Mairesse and P. Mohnen (2010) Measuring the returns to R&D. In: B.H. Hall and N. Rosenberg (eds.) *Handbook of the Economics of Innovation. Volume 2*. Amsterdam, North-Holland, 1033-82.

[26] Helmers, C. (2019) Choose the neighbor before the house: Agglomeration externalities in a UK science park. *Journal of Economic Geography* 19: 31-55.

[27] Katz, B. and J. Bradley (2013) *The Metropolitan Revolution. How Cities and Metros Are Fixing Our Broken Politics and Fragile Economy*. Washington, DC, Brookings.

[28] Link, A.N. and J.T. Scott (2003) U.S. science parks: The diffusion of an innovation and its effects on the academic missions of universities. *International Journal of Industrial Organization* 21: 1323-56.

[29] Link, A.N. and J.T. Scott (2007) The economics of university research parks. *Oxford Review of Economic Policy* 23: 661-74.

[30] Lucas, R.E. Jr. (1988) On the mechanics of economic development. *Journal of Monetary Economics* 22: 3-22.

[31] Lucas, R.E. Jr. and E. Rossi-Hansberg (2002) On the internal structure of cities. *Econometrica* 70: 1445-76.

[32] Lychagin, S., J. Pinkse, M.E. Slade, and J. Van Reenen (2016) Spillovers in space: Does geography matter? *Journal of Industrial Economics* 64: 295-335.

[33] Marshall, A. (1890) *Principles of Economics*. London, Macmillan. 8th edition published in 1920.

[34] McCarthy, I.P., B.S. Silvestre, A. von Nordenflycht, and S.M. Breznitz (2018) A typology of university research park strategies: What parks do and why it matters. *Journal of Engineering and Technology Management* 47: 110-122.

[35] Ogawa, M. and M. Fujita (1980) Equilibrium land use patterns in a nonmonocentric city. *Journal of Regional Science* 20: 455-75.

[36] O'Hara, D.J. (1977). Location of firms within a square central business district. *Journal of Political Economy* 85: 1189-207.

[37] Peter, A. and C. Ruane (2020) The aggregate importance of intermediate input substitutability. Princeton University, memo.

[38] Romer, P. (1986) Increasing returns and long-run growth. *Journal of Political Economy* 94: 1002-37.

[39] Rosenthal, S. and W. Strange (2004) Evidence on the nature and sources of agglomeration economies. In: J.V. Henderson and J.-F. Thisse (eds.) *Handbook of Urban and Regional Economics. Volume 4*. Amsterdam, North-Holland, 2119-71.

[40] Saxenian, A. (1994) *Regional Advantage: Culture and Competition in Silicon Valley and Route 128*. Cambridge, MA, Harvard University Press.

[41] Siegel, D.S., P. Westhead, and M. Wright (2003) Assessing the impact of university science parks on research productivity: Exploratory firm-level evidence from the United Kingdom. *International Journal of Industrial Organization* 21: 1357-69.

[42] Smith, T. (1978) A cost-efficieny principle of spatial interaction behavior. *Regional Science and Urban Economics* 8: 313-37.

Figure 1. Bid Rent Schedules with a Science Park