GOVERNANCE AND THE EFFICIENCY OF ECONOMIC SYSTEMS
GESY

Discussion Paper No. 64

Labor Pooling in R&D Intensive Industries

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September 2005

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Financial support from the Deutsche Forschungsgemeinschaft through SFB/TR 15 is gratefully acknowledged.

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September 12, 2005

Abstract

We investigate firms' incentives to locate in the same region to gain access to a large pool of skilled labor. Firms engage in risky R&D activities and thus create stochastic product and implied labor demand. Agglomeration in a cluster is more likely in situations where the innovation step is large and the probability for a firm to be the only innovator is high. When firms cluster, they tend to invest more and take more risk in R&D compared to spatially dispersed firms. Agglomeration is welfare maximizing, because expected labor productivity is higher and firms choose a more efficient, technically diversified portfolio of R&D projects at the industry level. (JEL: L13, O32, R12)

*We gratefully acknowledge financial support from the Deutsche Forschungsgemeinschaft (grant SPP 199, Sta 169/9-3, as well as SFB-TR 15) and the European Commission under the TMR network "The Evolution of Market Structure in Network Industries" (FMRX-CT98-0203) and under the RTN Network "The Economic Geography of Europe: Measurement, Testing and Policy Simulations" (HPRN-CT-2000-00069). We would like to thank Gilles Duranton, Rikard Forslid and seminar participants at Pompeu Fabra (Barcelona) and at the RTN meeting in Villars for valuable comments on earlier drafts. All remaining errors are ours.

1 Introduction

Clusters play a central role in the spatial organization of some of the world's most dynamic and R&D intensive industries. The best known example is Silicon Valley that during the 90s was home to 20 per cent of the world's 100 biggest electronics and software companies (*Business Week*, August 5, 1997). Other well-known examples are the biotech cluster in La Jolla (California), the neuroscience cluster in Oxford (UK) and the automotive industry in the Stuttgart region (Germany). While these examples are interesting in themselves, there is also more systematic evidence showing that firms in R&D intensive industries tend to cluster their innovative as well as their productive activities more than other firms (Audretsch and Feldman, 1996).

The success of some of these clusters has been remarkable. In spite of ups and downs in employment during the 90s of the last century, the employment growth rate in Silicon Valley outpaced with an impressive 15 per cent the U.S. national employment growth rate, and the mean income was 50 per cent higher than the national figure (Audretsch, 1998). The performance of Silicon Valley and other leading high-tech clusters has promoted a worldwide interest in replicating them. Billions of dollars were spent by local, regional and national governments to promote the formation of high-tech clusters. Yet overall success rates were low, indicating that the forces behind these agglomeration processes are more subtle than thought of heretofore.

In his Principles, Marshall (1920) argued that firms enjoy a number of benefits when locating in a cluster.[1] Firstly, the high demand for intermediate inputs allows upstream suppliers to achieve a higher degree of specialization, leading to a more efficient division of labor within the industry and lower prices due to decreasing marginal cost (Stigler, 1951; Krugman, 1991b).

Secondly, technology spillovers enable firms inside a cluster to share information and knowledge. There is empirical evidence demonstrating that firms' productivity increases due to technology spillovers with increasing geographical proximity (Acs et al., 1994; Almeida and Kogut, 1999; Jaffe et al., 1993; summarized in Audretsch and Feldman, 2004). Recently, a number of authors have analyzed spillover driven clustering from a theoretical perspective (Combes and Duranton, 2005; Fosfuri and Rønde, 2004; Saint-Paul, 2003).

Thirdly and finally, the concentration of firms attracts a 'deep' pool of laborers, which is the benefit from clustering that we focus on in this paper. Marshall argued that firms have incentives to locate in the same region when they face imperfectly correlated stochastic

[1] See Duranton and Puga (2004) for an excellent survey of the microeconomics of clusters.

labor demands. Firms blessed with high output and labor demand can draw workers at low cost from a large local labor market pool. Labor pooling thus provides firms with a more elastic labor supply and workers with more job security. Although labor pooling probably is the agglomeration benefit that has received the least attention in the literature, empirical work suggests that it plays an important role for firms' location decisions. Indeed, Rosenthal and Strange (2002) regress an index of spatial industry localization on proxies for the three above mentioned agglomeration benefits and find that the evidence is strongest for the labor pooling argument.

Marshall's labor pooling argument was first formalized in a stylized model by Krugman (1991a, Ch. 2 and App. B). He analyzed location equilibria with n firms who produce under decreasing returns to scale and face exogenous firm-specific productivity shocks. For fixed regional labor supply, the expected wage is increasing in the number of firms, because firms employ on average less workers and produce more efficiently. At the same time, more firms in a region also attract more workers, because of higher wages. Therefore, firms, upon deciding their location, have to trade-off a larger labor supply with a higher labor cost. We further explore the labor pooling argument by analyzing an explicit source of firm-specific shocks in the form of stochastic research and development (R&D) outcomes. Our model unveils a new benefit of labor pooling and offers novel, empirically verifiable predictions.

We consider a simple setup where two firms supply to a competitive world market. Firms have access to a common technology that allows them to produce a basic quality, but undertake risky R&D to improve on their product quality. The R&D shocks translate into stochastic product, and therefore labor demands. Confronted with location decisions before the outcome of these shocks becomes known, the firms decide to either locate separately in small labor markets, or, followed by their labor pool, to jointly locate in a large labor market. Firms may prefer separate locations in spite of the smaller labor supply, in order to enjoy monopsony power in the labor markets and to avoid the competition for laborers that arises under agglomeration.

We first look at a situation where innovations are the result of an exogenous R&D process. We show that agglomeration in a cluster only occurs if, after the realization of the R&D shocks, firms are likely to end up in an asymmetric situation where one of the firms pulls significantly ahead in the R&D race. If this outcome arises *ex-post*, the leading firm is able to enjoy the large labor supply at relatively low wages, because competition in the labor market from the lagging firm is weak. By contrast, if firms produce products of similar qualities, most of their profits are destroyed by labor market competition. Labor pooling has thus two opposing effects on profits. It allows the leading firm to expand its production, which increases expected profits and constitutes the agglomerative force in our model. At the same time, competition in the labor market dilutes profits, which works against agglomeration.

We then endogenize firms' R&D strategies and thereby, implicitly, the labor demand shocks. In particular, we analyze the two most important dimensions of R&D decisions, namely the size and the technical risk of R&D investment. Interestingly, upon agglomeration, *ex-ante* identical firms generically choose asymmetric R&D strategies to avoid joint success and to reduce labor market competition. This contributes to a higher variance of average firm productivity in agglomerations.

The welfare analysis shows that within our framework agglomeration of the firms is always the preferred industry outcome. The superiority of a cluster relative to dispersed locations in terms of welfare stems from two sources. Firstly, successful innovations are applied over a larger base of workers due to a deeper labor pool (a 'labor productivity effect'). Secondly, agglomeration in a cluster allows for a better organization of R&D programs within the industry (an 'R&D portfolio effect'). This effect is the result of firms' endogenous choice of R&D strategy, and it represents a benefit of labor pooling that has not been discussed heretofore. The intuition is that if the firms locate together in a cluster and both experience R&D success, one of the innovations represents wasteful duplication of R&D efforts. The asymmetric equilibrium strategies that reduce the likelihood of joint success increase thus the efficiency of the R&D portfolio at the industry level by reducing duplication. Since there are clear cut regimes under which firms separate in equilibrium, there is too much locational separation relative to the welfare optimum.

Apart from Krugman (1991a), Stahl and Walz (2001) is the only other formal model of labor pooling known to us. Stahl and Walz introduce both firm-specific and sector-specific (exogenous) shocks and analyze whether firms locate together with firms belonging to the same or to a different sector. There is also a small literature on firms' location decisions relative to localized labor markets. However, Topel (1986), Baumgardner (1988), or more recently Picard and Toulemonde (2000) all focus on issues different from ours, such as workers' migration incentives, division of labor as changing with labor market size, and asymmetric agglomeration as the result of minimum wages, respectively.

The remainder of the paper is organized as follows: In the section 2, we present our baseline model of labor pooling with exogenous R&D strategies. In Section 3, we endogenize R&D investment decisions and derive and characterize the equilibria of the game. In section 4, we analyze a variant of the model where firms choose the risk-return profile of the R&D rather than the R&D investment level. We conclude by discussing implications of our analysis and possible extensions. All relevant proofs are relegated to an Appendix.

2 A Simple Model of Labor Pooling

2.1 The Model Set-Up

There are two firms 1 and 2, and two locations. The firms produce with a one-to-one production function, so that L_i units of labor employed by firm i at wage w_i result in the identical output quantity y_i. With respect to their output, the firms are price takers in a world market. The price obtained depends on the quality of the product. For simplicity, we assume that the price p_i fetched by firm i is equal to the quality of its product q_i.[2] The firms' marginal production cost net of wages is normalized to zero, and fixed costs are sunk.

The firms are initially endowed with a technology to produce a good of quality v. They may benefit from the outcome of a stochastic R&D process that for the moment is costless. If the R&D project is successful, the product's quality is increased to $v + \Delta$, with $\Delta > 0$. If the R&D project is unsuccessful, the firm has to produce the initial quality. We assume in this section the simplest possible R&D process where there is an exogenous and independent probability of success ρ for each firm.

In specifying labor supply, we follow the simple approach taken by Krugman (1991a). There is a mass of L identical workers with industry-specific skills in the economy. Before accepting a job, they are perfectly mobile between the two locations. However, once settled in one region, the costs of migration become prohibitive.[3] The workers are risk-neutral and choose the location maximizing their expected wage. The opportunity wage outside the industry for the workers is $\overline{u} < v$, i.e. industry production is efficient with the initial product quality.

The firms simultaneously choose their location. Henceforth we refer to outcomes of the location subgame in which firms locate together as 'agglomeration', and to outcomes with differing locations as 'separation'. If the firms agglomerate, they compete in wages for the skilled workers in the region. Firms simultaneously set wages and workers choose either the firm offering the higher wage, or take the outside opportunity. In case of a tie at a wage that is preferred to the outside option, workers split equally across the firms. If the firms choose separate locations, they behave as monopsonists in their respective local labor market.

The timing of the game is as follows: 1) firms choose their location, 2) workers locate, 3) R&D outcomes are realized, 4) firms set wages and workers are hired, and 5) production takes place and profits are realized. Our timing reflects that location decisions involve a longer

[2] This price would also be obtained if the two firms were monopolists in their respective market and $N \geq L$ consumers endowed with a utility function of $U = q - p$ would buy at most one unit of the good.

[3] Introducing non-prohibitive *ex-post* migration costs would not affect the qualitative nature of our results.

term commitment relative to R&D decisions, which in turn are less flexible than allocation decisions involving wages.

2.2 Equilibrium Analysis

Suppose that firms have chosen separate locations. As each firm is a monopsonist in its local labor market, workers are paid a wage that matches their outside opportunity $\overline{u}$, and this independently of the R&D outcome. Therefore, *ex-ante*, workers are indifferent between settling in the two regions, and the expected local labor supply is $L/2$. Then, firm i's expected profits under separation are

$$\begin{aligned} E(\pi_i^S) &= \rho(v+\Delta-\overline{u})\frac{L}{2}+(1-\rho)(v-\overline{u})\frac{L}{2} \\ &= \frac{L}{2}(v-\overline{u}+\rho\Delta). \end{aligned} \tag{1}$$

Obviously, the firms' profits increase in the number of workers available, as well as in the expected product quality net of the minimum wage, $\overline{u}$.

Suppose now that firms have agglomerated in one region. The wage resulting from firms' competition in the labor market depends on the outcome of the R&D process of both firms.

Lemma 1 *Consider the labor market equilibrium when firms agglomerate.*
i) If both firms produce at the same quality $q \geq v$, then the equilibrium wages are $w_i^* = w_j^* = q$. Firms make no profit.
ii) If firm i produces at quality $v+\Delta$ and firm j at quality v, then the equilibrium wages are $w_i^* = v+\varepsilon$ and $w_j^* = v$, respectively. All workers supply to firm i. Firm i's profit per worker is Δ, and firm j makes no profit.

Hence under agglomeration the firms' competition for labor shifts rents to the workers. When product qualities are symmetric, no matter whether both firms have innovated or not, all profits are competed away in the labor market. By contrast, when only one firm innovates, the successful firm drives the low quality firm out of the market and employs all available workers at a wage above the workers' outside opportunity. The expected profits of firm i under agglomeration are therefore

$$E(\pi_i^A) = \rho(1-\rho)\Delta L. \tag{2}$$

Profits increase in the probability that only one firm is successful, $\rho(1-\rho)$, in the size of the labor pool, and in the innovation step.

In the first stage of the game, firms simultaneously choose their location on the basis of expected profits. Comparing (1) and (2), the Nash equilibrium in locations can be summarized as follows.

Proposition 1 *Agglomeration is the unique location outcome if $\rho < 1/2$ and*

$$\Delta \geq \widetilde{\Delta} \equiv \frac{v - \overline{u}}{\rho(1 - 2\rho)}. \tag{3}$$

Otherwise, the firms choose separate locations.

The profits of a firm can come from two sources: the basic product quality available at the industry level and firm specific product innovation. Under separation, both the basic product quality and the innovation contribute to expected profits. Under agglomeration, however, successful innovation is the only source of rents, because the profits that could accrue from the basic product quality are competed away in the labor market. Hence, a necessary condition for agglomeration to be the preferred option is that the expected profits from successful innovation efforts must be greater than under separation.

Explaining the location trade-off in a different way, agglomeration has two opposing effects on profits. On the one hand, it induces the formation of a large labor pool. Therefore the firm with the higher product quality can expand its production more than under separation, which increases expected profits. This is the agglomerative force. On the other hand, wages increase via tougher competition for workers. Wage competition under agglomeration thus constitutes the deglomerative force in the model.

Keeping these two forces in mind, the comparative statics of the model are easily understood. Under agglomeration a firm is only able to hire workers at a profitable rate if it pulls ahead in the R&D race and makes its workers more productive than the rival's. Consequently, agglomeration is more profitable if the innovation step, i.e. the productivity advantage of the winning firm, is large. Agglomeration is also more likely if the R&D hazard rate is neither too low (which would render innovation unlikely) nor too high (which renders likely simultaneous innovation by both firms). The $\Delta-$threshold of Proposition 1 takes its minimum value at a hazard rate of $1/4$, and separation equilibrium always obtains for $\rho \geq 1/2$. This relationship is illustrated in Figure 1. Finally, wage competition under agglomeration destroys all rents to firms from the initial technology. Thus, separation becomes the more attractive the higher is $v - \overline{u}$. This can also be seen from Figure 1 where the region of the parameter space for which agglomeration is the equilibrium outcome is smaller for the higher value of $v - \overline{u}$.

Turning to a welfare comparison, we have that expected social surplus, the sum of workers' rents and firms' profits, is maximized when firms agglomerate. Under agglomeration all available labor produces the higher quality good if at least one of the firms is successful in R&D. Under separation this is possible only if both firms are successful. Agglomeration has therefore the advantage over separation that workers are always put to their most productive use. We will refer to this agglomeration benefit as the '*labor productivity effect*'. The welfare

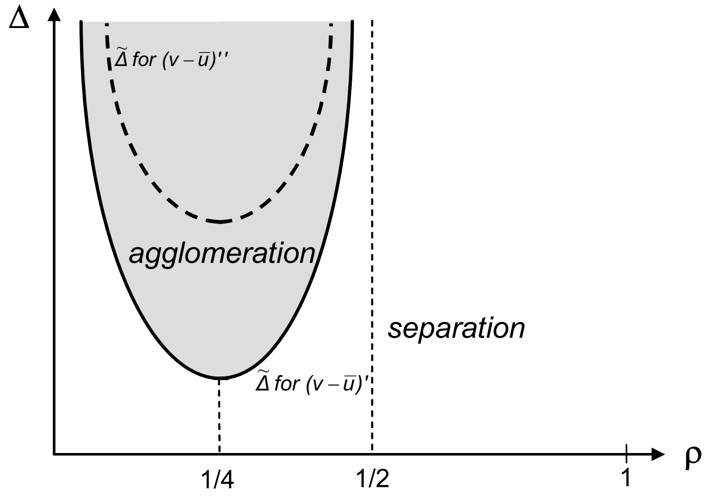

Figure 1: *Location equilibrium with exogenous R&D sucess probabilities for two different values of* $v - \overline{u}$, $(v - \overline{u})' < (v - \overline{u})''$.

implication of the location equilibrium in Proposition 1 is straightforward. There is (weakly) too little agglomeration in equilibrium.

Albeit extremely simple, this benchmark model captures the central features of Marshall's labor pooling argument. Furthermore, it provides us with a framework that lends itself to model endogenous R&D and to explore the interaction between location and innovation. Before continuing to these issues, we would like to mention that the model can be reinterpreted as a dynamic R&D model with catching-up in technology. Consider an infinite horizon model in discrete time where the firms and workers choose their locations at the beginning of the game. Innovations occur in discrete jumps (maximally one per period) along a 'quality ladder' à la Grossman and Helpman (1991) of the type $q_i = (1+\Delta)q_{i-1}$. If one firm pulls ahead in a period, the laggard catches up before the beginning of the next period. That is, firms start the following period with equal qualities. It can be shown that such a dynamic R&D race produces the same threshold $\widetilde{\Delta}$ as in Proposition 1.

3 Endogenous R&D Investment

In the benchmark model firms' location decisions were driven by exogenous shocks. These shocks were referred to as innovations, but they could equally well be interpreted as demand shocks. In this and the following section we take seriously the former interpretation, and endogenize the shocks by explicitly modeling firms' R&D decisions. This allows us to bring together two aspects heretofore not considered together, namely the choice of location, and the choice of research technology. The aim is to analyze the interplay between labor market competition and R&D decisions and how this, in turn, influences equilibrium location choices and welfare conclusions.

In the industrial organization literature, two main dimensions of firms' R&D activities are identified: i) how much money to invest in R&D towards improvements relative to existing products; and ii) how ambitious a R&D project to target.[4] In the present section we look at a situation where the investment decision monotonically increases the probability of R&D success and the innovation size. In the ensuing section we consider, at fixed investment level, a trade-off between success probability and innovation size.

3.1 Model with R&D Investment

In the simple model presented in the previous section, R&D was characterized by two exogenous parameters, ρ, the probability of a successful innovation, and Δ, its size. Without alluding to specific examples it is difficult to say whether R&D investment affects ρ, Δ, or both. We therefore start from a fairly general R&D technology and then look at two focal, parameterized examples.

Returning to the specification of a general R&D technology, let firm i choose an R&D intensity ϕ_i resulting in a probability of success $\rho(\phi_i)$ and an innovation size $\Delta(\phi_i)$. Both $\rho(\phi_i)$ and $\Delta(\phi_i)$ are C^2-functions. Let $\rho(\cdot)$, $\Delta(\cdot) > 0$ for $\phi_i > 0$ and $\rho'(\cdot)$, $\Delta'(\cdot) \geq 0$ with at least one strictly positive slope. The cost of employing ϕ_i is specified by the C^2-function $g(\phi_i)$ where $g(0) = g'(0) = 0$ and $g''(\cdot) > 0$. It is assumed that $g(\cdot)$ is sufficiently convex so that the profit function of firm i is concave for $\phi_i < \phi_j$ and for $\phi_i > \phi_j$, and that corner solutions are excluded.[5] Notice that in this formulation - and in contrast to section 4 - a given R&D intensity ϕ_i results in separately determined ρ_i and Δ_i. Hence the firm cannot trade off a higher ρ_i against a lower Δ_i, or vice versa.

In our baseline model the profits of the two firms were symmetric, since ρ and Δ were identical for both firms. This led to a simple solution to the locational choice problem in the first stage of our game, as firms always agreed on whether to locate jointly or separately. It turns out that with endogenous R&D investments, equilibrium strategies and resulting profits will be generically asymmetric under agglomeration. Hence situations can arise in which one firm prefers separation and the other one agglomeration. Since firms are identical *ex-ante*, we deal with this possibility by introducing an additional stage in our timing: After firms have

[4]See, e.g., Bhattacharya and Mookherjee (1986) or Dasgupta and Maskin (1987).

[5]By this we assume that the profit function is piecewise concave but not necessarily globally concave.

chosen locations, but before they choose R&D strategies, nature determines which one of the firms will play the more research intensive strategy. The two firms are equally likely to be assigned the role of the research intensive firm. At the stage where locations are chosen, the firms' expected profits are thus symmetric and the location choice can be analyzed as before.

3.2 Equilibrium Analysis

Towards an analysis of this extended model, suppose that in the first stage of the game the firms have chosen separate locations. The expected profit of firm i is now given by

$$\pi^S(\phi_i) = \rho(\phi_i)(v - \overline{u} + \Delta(\phi_i))L/2 + (1 - \rho(\phi_i))(v - \overline{u})L/2 - g(\phi_i),$$

and the optimal research intensity $\phi^{S,*}$ solves the first-order condition

$$\rho'(\phi^{S,*})\Delta(\phi^{S,*})L/2 + \rho(\phi^{S,*})\Delta'(\phi^{S,*})L/2 - g'(\phi^{S,*}) = 0. \tag{4}$$

Suppose now instead that firms have chosen to agglomerate in the first stage of the game. Then, the outcome of the labor market competition depends on the outcome of the stochastic R&D processes. A firm can draw all workers from the labor pool if its R&D project is the only successful one in the industry. At the same time, for $\Delta'(\phi) > 0$, the firm investing more aims for a higher product quality and employs all skilled laborers in the event that both firms' R&D projects are successful. Therefore, the expected profit of any firm i can be written as:

$$\pi_i^A(\phi_i, \phi_j) = \rho(\phi_i)(1 - \rho(\phi_j))\Delta(\phi_i)L - g(\phi_i) + \begin{cases} 0 & \text{if } \phi_i \leq \phi_j, \\ \rho(\phi_i)\rho(\phi_j)(\Delta(\phi_i) - \Delta(\phi_j))L & \text{otherwise.} \end{cases}$$

Suppose without loss of generality that $\phi_i \leq \phi_j$. The first-order condition for the low-investment firm i is

$$(1 - \rho(\phi_j^{A,*}))\left[\rho'(\phi_i^{A,*})\Delta(\phi_i^{A,*}) + \rho(\phi_i^{A,*})\Delta'(\phi_i^{A,*})\right] L - g'(\phi_i^{A,*}) = 0, \tag{5}$$

while for the high-investment firm j it is

$$\left[\rho'(\phi_j^{A,*})\Delta(\phi_j^{A,*}) + \rho(\phi_j^{A,*})\Delta'(\phi_j^{A,*}) - \rho'(\phi_j^{A,*})\rho(\phi_i^{A,*})\Delta(\phi_i^{A,*})\right] L - g'(\phi_j^{A,*}) = 0. \tag{6}$$

It is easy to verify that the firms' R&D investment choices are strategic substitutes.[6] An increase in one firm's R&D investment reduces the marginal value of the other firm's

[6] Check that for two firms with $\phi_i \leq \phi_j$ it holds that $\partial^2\pi_i^A(\phi_i, \phi_j)/(\partial\phi_i\partial\phi_j) = \partial^2\pi_j^A(\phi_i, \phi_j)/(\partial\phi_j\partial\phi_i) = -\rho'(\phi_j)(\rho'(\phi_i)\Delta(\phi_i) + \rho(\phi_i)\Delta'(\phi_i)) < 0$.

investment by decreasing the probability of having the only successful R&D project. Also, for the higher investment firm j, investment by firm i decreases profits by reducing j's efficiency advantage in case both firms are successful.

The following proposition characterizes the R&D equilibrium under agglomeration.

Proposition 2 *Suppose that $g(\cdot)$ is sufficiently convex, and consider the equilibrium in R&D investment strategies $(\phi_i^{A,*}, \phi_j^{A,*})$ when firms agglomerate.*
(i) If $\Delta'(\phi^{A,*}) = 0$, then there exists a unique, symmetric, pure-strategy equilibrium, $\phi_i^{A,*} = \phi_j^{A,*} = \phi^{A,*}$ in which the equilibrium investment satisfies

$$(1 - \rho(\phi^{A,*}))\rho'(\phi^{A,*})\Delta(\phi^{A,*})L - g'(\phi^{A,*}) = 0. \tag{7}$$

(ii) If $\Delta'(\phi^{A,*}) > 0$, then there exists a generically unique pure-strategy equilibrium with $\phi_i^{A,*} < \phi_j^{A,*}$ in which the equilibrium investment levels satisfy (5) and (6).

The equilibrium in investment strategies conditional upon firms' agglomeration exhibits some interesting properties. Specifically, as long as $\Delta(\cdot)$ is a strictly increasing function, the *ex-ante* symmetric firms choose asymmetric R&D investments. The reason is that the marginal return to R&D investment increases discretely as a firm's investment becomes larger than its competitor's. The firm then produces a higher quality than its competitor when both firms are successful and wins the labor market bidding for skilled laborers, which increases the marginal return to R&D.[7] This property induces firms to optimally differentiate their R&D strategies. The high investment firm benefits from more frequent and better innovation and from full access to the labor pool in case of joint R&D success. The low investment firm is better off saving on R&D expenditures, even if it only gains access to the entire labor pool in situations where it is the sole innovator. Notwithstanding this optimal differentiation of R&D strategies, it is easy to show that, in equilibrium, the high investment firm j has higher expected profits than firm i.[8]

Finally, given the fairly general functional form setup of the R&D technology, it is noteworthy that Proposition 2 implies both existence and uniqueness of a pure-strategy R&D equilibrium.[9]

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[7] Note, however, that the firm's payoff remains continuous at this investment level, because the profit margin (price - wage) reflects the difference in product quality.

[8] Verify that $\partial\pi_i^A(\phi_i, \phi_j)/\partial\phi_j < 0$. Using this, the fact that $\phi_i^{A,*} < \phi_j^{A,*}$, and a revealed preference argument, we have that $\pi_i^A(\phi_i^{A,*}, \phi_j^{A,*}) < \pi_i^A(\phi_i^{A,*}, \phi_i^{A,*}) = \pi_j^A(\phi_i^{A,*}, \phi_i^{A,*}) \leq \pi_j^A(\phi_i^{A,*}, \phi_j^{A,*})$.

[9] To be precise, we are able to link the equilibrium and welfare analysis via the first-order conditions. We then show that if $g(\cdot)$ is sufficiently convex, then there exists a unique solution to the welfare problem, which implies that a unique equilibrium in pure strategies exists.

Let us now turn to the determination of equilibrium location choices. By the assumption that nature chooses with identical probability 1/2 whether upon agglomeration firm i is the stronger or the weaker investor in R&D, agglomeration is the equilibrium outcome if and only if

$$\pi_i^A(\phi_i^{A,*}, \phi_j^{A,*}) + \pi_j^A(\phi_j^{A,*}, \phi_i^{A,*}) \geq 2\pi^S(\phi^{S,*}). \quad (8)$$

Otherwise, the firms will choose separate locations. The next proposition compares equilibrium investments under separation and agglomeration and further characterizes the location equilibrium.

Proposition 3 *Compare R&D investments and expected profits from innovation under the two location choices:*
(i) In a symmetric equilibrium, $\rho(\phi^{A,*}) < 1/2$ *is a necessary and sufficient condition for firms to invest more in and to earn higher profits from R&D under agglomeration than under separation.*
(ii) In an asymmetric equilibrium with $\phi_i^{A,*} < \phi_j^{A,*}$, $\rho(\phi_j^{A,*}) < 1/2$ *is a sufficient condition for both firms to invest more in and to earn higher profits from R&D under agglomeration than under separation.*
(iii) If the expected equilibrium profits accruing from R&D are higher under agglomeration than under separation, then there exists a unique level $\psi > 0$ *such that in equilibrium,* $v - \overline{u} < \psi$ *implies agglomeration, and* $v - \overline{u} > \psi$ *implies separation.*

As detailed in the discussion of the baseline model in section 2, expected profits under separation are composed of the certain profits from the basic technology and the expected profits from innovation, while under agglomeration firms only earn profits from innovation. Thus, for agglomeration to be preferred, the profits from innovation under agglomeration must exceed the profits from innovation under separation, and the basic technology must not be too profitable. Point *(iii)* of Proposition 3 makes this argument precise.

Points *(i)* and *(ii)* of the proposition reflect the trade-off between innovating for a labor pool of half the size under separation versus the loss of innovation rents from competition under agglomeration. A firm invests more in R&D under agglomeration and ends up with higher expected profits from innovation if the equilibrium hazard rate of its competitor is less than 1/2. Though the conditions $\rho(\phi^{A,*}) < 1/2$ and $\rho(\phi_j^{A,*}) < 1/2$ refer to endogenous rather than exogenous parameters,[10] it is clear that these conditions hold in equilibrium when it is

[10] We have formulated them this way in order to preserve the comparability of the results with those derived in the other model versions.

not feasible or too expensive to increase the hazard rate beyond 1/2, i.e. $\lim \rho(\phi) < 1/2$ as $\phi \to \infty$, or $g(\phi) \to \infty$ as $\phi \to \rho^{-1}(1/2)$. This will be illustrated in more detail in Example I below.

Note also that in an asymmetric equilibrium, $\rho(\phi_j^{A,*}) < 1/2$ is not a necessary condition for agglomeration to occur. The expected *ex-ante* profits from R&D can be higher under agglomeration for $\rho(\phi_j^{A,*}) > 1/2$ even if the *ex-post* profit of firm i, which is assigned the less attractive role as the low invest firm, is higher under separation. This point will be further detailed in Example II below.

3.3 Welfare

We now turn to the welfare properties of the equilibrium characterized in the previous section. Under separation firms operate as monopsonists and appropriate all local rents. From this follows directly that given locational separation, the equilibrium R&D intensities maximize total welfare.

The welfare analysis is more involved under agglomeration because there are competing effects at play. Firms no longer capture all rents that accrue from their R&D investment. Instead some of these rents go to the workers in the form of higher wages. This tends to reduce the R&D investments below the welfare maximizing level. At the same time, however, there is a strategic effect at play. A firm does not internalize the negative effect that its R&D investment has on the competitor's profits, which pushes towards overinvestment in R&D. *A priori*, it is unclear how these effects play out and whether there is underinvestment or overinvestment in R&D.

Aggregate welfare is specified by

$$W^A(\phi_i, \phi_j) = \left[v - \overline{u} + \rho(\phi_j)\Delta(\phi_j) + \rho(\phi_i)(1 - \rho(\phi_j))\Delta(\phi_i)\right] L - g(\phi_i) - g(\phi_j).$$

Suppose that $W^A(\phi_i, \phi_j)$ is globally concave in ϕ_i and ϕ_j for $\phi_i \leq \phi_j$, which holds if $g(\cdot)$ is sufficiently convex. Then it is easy to verify that the first-order conditions characterizing the welfare maximizing R&D intensities are identical to (5) and (6). Hence the R&D intensities chosen by the firms in equilibrium are welfare maximizing, i.e. the two effects leading to underinvestment and overinvestment, respectively, cancel each other out. A more formal explanation of this result is the following: The expected contribution of firm i to social welfare is $E[Max\{q_i - q_j, 0\}L - g(\phi_i)]$, which is equal to firm i's expected profit. Therefore, the firm has the right incentive to invest in quality improvement. Although interesting, we do not wish to over-emphasize this result as it clearly represents a knife's edge case. Changes in the specification of the model, for example in the mode of competition in the labor or output markets, could affect the relative strength of the two opposing effects. As a result, equilibrium R&D investments would no longer be welfare optimal.

The next proposition summarizes the welfare analysis of R&D investments and assesses the efficiency of location choices.

Proposition 4 *Suppose that $g(\cdot)$ is sufficiently convex such that the welfare function is globally concave in ϕ_i and ϕ_j for $\phi_i \leq \phi_j$. Then*
(i) conditional upon locations, firms choose the welfare maximizing R&D intensities,
(ii) welfare is maximized when firms agglomerate.

Towards assessing the efficiency of the location equilibrium, it is useful to decompose the welfare difference between agglomeration and separation into two effects, an *R&D portfolio effect* and a *labor productivity effect*,

$$W^A(\rho_i^{A,*}, \rho_j^{A,*}) - W^S(\rho^{S,*}, \rho^{S,*}) = \underbrace{W^A(\rho_i^{A,*}, \rho_j^{A,*}) - W^A(\rho^{S,*}, \rho^{S,*})}_{\text{R\&D portfolio effect}} + \underbrace{W^A(\rho^{S,*}, \rho^{S,*}) - W^S(\rho^{S,*}, \rho^{S,*})}_{\text{Labor productivity effect}}$$

The labor productivity effect captures the welfare benefit of agglomeration for constant R&D strategies. As discussed in section 2.2, this effect is positive because under agglomeration the higher quality firm can expand production by hiring all workers. The R&D portfolio effect represents the welfare benefit of agglomeration, because labor pooling allows for a more efficient diversified R&D portfolio at the industry level.[11] To the best of our knowledge, the R&D portfolio effect is novel to the labor pooling literature.

The major difference between the equilibrium R&D strategies under the two locational choices is that firms choose asymmetric R&D investments under agglomeration but symmetric R&D investments under separation. To see why asymmetric investments lead to a more efficient R&D portfolio, suppose that firms would choose symmetric investment levels. Then, if both firms were successful, the R&D investment of one of the firms would be wasted, i.e. would not contribute to welfare. Notice that this is not the case under separation as the firms do not share a common pool of workers. Keeping total investments constant but allocating them asymmetrically reduces the problem of wasteful R&D duplication under agglomeration. The investment of the low quality firm is still wasted if the high quality firm is successful. However, since the low quality firm invests less compared to the situation of symmetric investments, that waste is reduced. Of course, this argument provokes the question of why it

[11]Since in equilibrium firms choose the welfare maximizing R&D investments, we have immediately that $W^A(\rho_i^{A,*}, \rho_j^{A,*}) \geq W^A(\rho^{S,*}, \rho^{S,*})$.

would not be efficient to allocate all investment to one firm to avoid duplication altogether. The reason is that there are decreasing returns to R&D investment at the firm level. Thus the allocation of R&D investment trades off the cost of asymmetric R&D investments due to decreasing returns to scale, against the cost of wasteful duplication of R&D efforts.[12]

While the welfare optimality of R&D investments rests on the specific assumptions made here, this appears not to be the case for the two effects underlying Proposition 4 (ii). The labor productivity effect relies on the more productive firm hiring more workers than the less productive firm under agglomeration. All reasonable specifications of labor market competition would yield this outcome, so this effect is clearly robust to different specifications of the model. The R&D portfolio effect arises, because firms have an interest in avoiding situations where joint R&D success cannibalizes the profits from innovation. Joint success is also undesirable from point of view of social welfare, because it entails wasteful duplication of R&D efforts. As public and private interests are aligned on this matter, it seems likely that also the R&D portfolio effect will remain positive for minor changes in the model.

In order to gain additional insights into the link between R&D strategies and location decisions, we have constructed two examples involving specific functions for $\rho(\cdot)$, $\Delta(\cdot)$, and $g(\cdot)$ so that the model could be solved in closed-form. We consider the two extreme cases, one where R&D investment increases only ρ, and another where it only increases Δ.

3.4 Example I: Endogenous Hazard Rate

Here, we consider a setup where firms choose the probability of achieving an innovation of constant size Δ. In particular, suppose that $\rho(\phi) = \phi$ and $g(\phi) = \gamma\phi^2/2$ where γ measures the marginal cost of R&D. We assume that $\gamma > \Delta L/2$, to exclude corner solutions. The equilibrium is derived in the same manner as above, so details are left out.

Since investment does not increase innovation size, there is a symmetric equilibrium also when firms choose to agglomerate. The investment in R&D per firm is $\phi^{S,*} = \Delta L/2\gamma$ and $\phi^{A,*} = \Delta L/(\Delta L + \gamma)$ under separation and agglomeration, respectively. This results in equilibrium profits

$$\begin{aligned}\pi_i^S(\phi^{S,*}) &= \frac{(v-\overline{u})L}{2} + \frac{\Delta^2 L^2}{8\gamma}, \\ \pi_i^A(\phi^{A,*}, \phi^{A,*}) &= \frac{\gamma \Delta^2 L^2}{2(\Delta L + \gamma)^2}.\end{aligned}$$

[12] Put differently, starting from a situation of symmetric investments, a small reallocation of investments from one firm to the other will result in a second-order reduction in R&D efficiency due to decreasing returns to scale but in a first-order reduction in R&D duplication. Therefore, the welfare maximizing R&D investments are asymmetric under agglomeration.

Comparing profits under agglomeration and separation, we find that firms agglomerate in the first stage if and only if

$$\pi_i^A(\phi^{A,*}, \phi^{A,*}) \geq \pi_i^S(\phi^{S,*}) \Leftrightarrow \frac{\Delta^2 L(\gamma - \Delta L)(3\gamma + \Delta L)}{4\gamma(\gamma + \Delta L)^2} \geqslant v - \overline{u}. \tag{9}$$

In Figure 2 equation (9) is plotted in (γ, Δ)-space. Notice that in this example the condition $\rho(\phi^{A,*}) < 1/2$ from Proposition 3 (i) is equivalent to $\gamma > \Delta L$. This implies that for all parameter values above the $\gamma = \Delta L$-line, firms invest more under agglomeration than under separation and the profits from innovation are higher when firms cluster. However, this must be weighed against the profits obtained under separation from producing the baseline product.

Since we can explicitly determine the relevant equilibrium values, it is easier to see the connection to the benchmark model of section 2 than in the more general setup. Firms agglomerate if two conditions are met: i) $\rho(\phi^{A,*})$ is intermediate between 0 and 1/2, and ii) Δ is sufficiently large compared to $v - \overline{u}$. The first condition is violated if the marginal cost of R&D, γ, is either too low (and therefore competition under agglomeration tough) or too high (such that the probability of using the larger labor pool under agglomeration is too small to outweigh the loss on the basic technology).

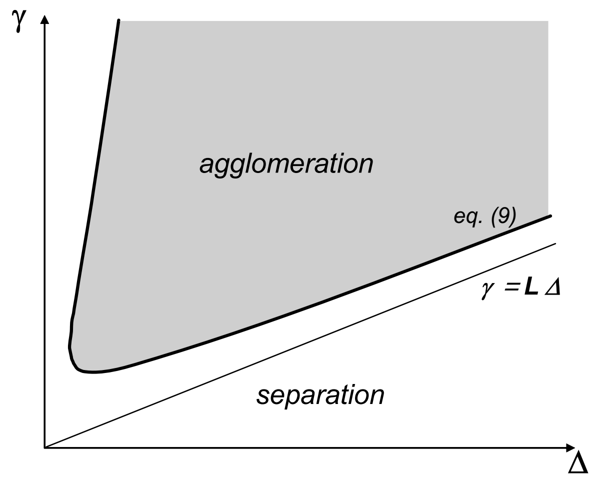

Figure 2: *Location equilibria with endogenous hazard rate.*

This and the following two examples also suggest a new and potentially testable implication concerning the variance in average product quality of the firms in the industry under agglomeration and separation. Define the average product quality (= productivity) as

$q = (q_1 + q_2)/2$. Then, the expected average product quality is given by

$$\begin{aligned} E[q] &= v + \rho_1\rho_2\frac{\Delta_1 + \Delta_2}{2} + \rho_1(1-\rho_2)\frac{\Delta_1}{2} + (1-\rho_1)\rho_2\frac{\Delta_2}{2} \\ &= v + \frac{\rho_1\Delta_1 + \rho_2\Delta_2}{2}, \end{aligned}$$

and its variance by

$$\begin{aligned} Var[q] &= \rho_1\rho_2(v + \frac{\Delta_1 + \Delta_2}{2} - E(q))^2 + \rho_1(1-\rho_2)(v + \frac{\Delta_1}{2} - E(q))^2 + \\ &\quad (1-\rho_1)\rho_2(v + \frac{\Delta_2}{2} - E(q))^2 + (1-\rho_1)(1-\rho_2)(v - E(q))^2 \\ &= \frac{1}{4}[\rho_1(1-\rho_1)\Delta_1^2 + \rho_2(1-\rho_2)\Delta_2^2]. \end{aligned}$$

In the specific example discussed here, $Var[q] = \Delta^2\rho^*(1-\rho^*)/2$. Therefore, the variance under agglomeration is higher (lower) than the variance under separation if $|\rho(\phi^{A,*}) - 1/2|$ $<$ $(>)$ $|\rho(\phi^{S,*}) - 1/2|$. However, we know from Proposition 3 that if $\rho(\phi^{A,*}) < 1/2$, then firms invest more in R&D under agglomeration so $1/2 > \rho(\phi^{A,*}) > \rho(\phi^{S,*})$. Similarly, if $\rho(\phi^{A,*}) > 1/2$, the firms invest less under agglomeration so $\rho(\phi^{S,*}) > \rho(\phi^{A,*}) > 1/2$. This leads to the empirical prediction that controlling for γ the variance in the average quality is larger under agglomeration than under separation.

3.5 Example II: Endogenous Innovation Size

Suppose now that firms choose the innovation size so that $\Delta(\phi) = \phi$ whereas the probability of success is constant, $\rho(\phi) = \rho$. Let the marginal cost of adding to the innovation size be quadratic as in the previous example.

With separate locations both firms choose the R&D intensity $\phi^{S,*} = \rho L/2\gamma$. The equilibrium profits are

$$\pi_i^S(\phi^{S,*}) = \frac{(v - \overline{u})L}{2} + \frac{\rho^2 L^2}{8\gamma}.$$

Under agglomeration equilibrium R&D intensities are asymmetric since $\Delta(\phi)$ is increasing in ϕ. Solving the first-order conditions, we find $\phi_i^{A,*} = (1-\rho)\rho L/\gamma$ and $\phi_j^{A,*} = \rho L/\gamma$. The more R&D intensive firm j, which produces the highest quality, increases its investment with higher success probability ρ. By contrast, the less R&D intensive firm i invests the most when the probability of being successful alone is maximized, i.e. at $\rho = 1/2$. Note also that firm j invests as much in R&D as the two firms together under separation. The resulting profits under agglomeration are

$$\pi_i^A(\phi_i^{A,*},\phi_j^{A,*}) = \frac{(1-\rho)^2\rho^2L^2}{2\gamma},$$
$$\pi_j^A(\phi_i^{A,*},\phi_j^{A,*}) = \frac{\rho^2L^2(1-2\rho(1-\rho))}{2\gamma}.$$

Comparing *ex-ante* profits, we find that the firms agglomerate if and only if

$$v-\overline{u} \leq \frac{\rho^2L}{4\gamma}\left(3-8\rho+6\rho^2\right)=\psi. \tag{10}$$

The graph of condition (10) is depicted in (γ,ρ)-space in Figure 3. The low investment firm makes higher profits from R&D under agglomeration than under separation if $\rho<1/2$. The high investment firm always earns higher profits from innovation than under separation. Since expected profits are increasing more rapidly in ρ under agglomeration than under separation, the threshold value of $v-\overline{u}$ below which firms agglomerate, ψ in (10), is also increasing in ρ. Furthermore, and as pointed out in the discussion of Proposition 3, the condition $\rho(\phi_j^{A,*})\leq 1/2$ is not necessary for agglomeration to occur, because firms choose asymmetric R&D strategies under agglomeration.

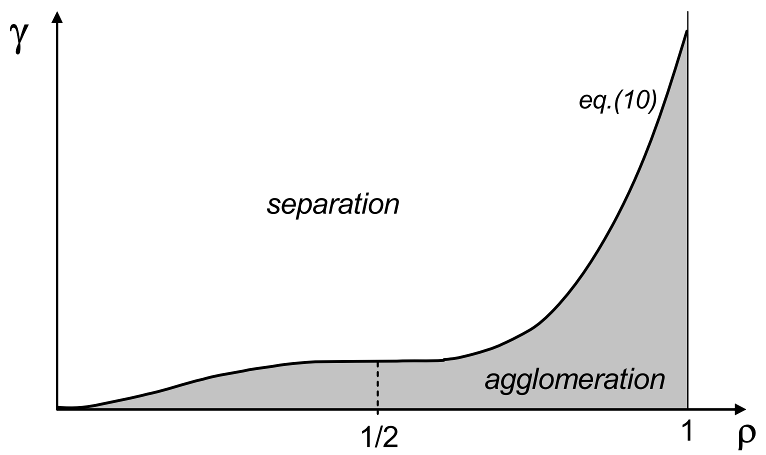

Figure 3: *Location equilibria with endogenous innovation size*

The variance in the average industry quality can be calculated as $Var[q]=\rho(1-\rho)[\Delta_i^2+\Delta_j^2]/4$. Using $\Delta_j^{A,*}=2\Delta^{S,*}$, it is now straightforward to show that the variance in the average industry quality is highest under agglomeration:

$$\underbrace{\rho(1-\rho)[(\Delta_i^*)^2+(2\Delta_S^*)^2]/4}_{\text{Variance under agglomeration}} > \underbrace{\rho(1-\rho)[(\Delta_S^*)^2+(\Delta_S^*)^2]/4}_{\text{Variance under separation}}.$$

The variance is higher under agglomeration both because firms invest more in R&D overall and because they choose asymmetric instead of symmetric strategies.

4 Endogenous Risk-Return Choice

The second important dimension in firms' R&D strategy is the choice between risk and return. Specifically, when should a firm target a R&D project with large innovation size but low probability of success, vs. a less ambitious project that is more likely to be successful? We consider a variant of the model where firms strategically choose the risk-return profile of their R&D project at given research outlay.

We start again from a general R&D technology and then look at a specific example. It is assumed that firm i chooses a level of technical risk ρ_i from $[\underline{\rho}, \overline{\rho}]$, $0 \leq \underline{\rho} \leq \overline{\rho} \leq 1$ resulting in an innovation of size $\Delta(\rho_i)$. Here, $\Delta(\cdot)$ is a C^2-function and $\Delta'(\cdot) < 0$. Finally, we assume that i) $2\Delta'(\rho_i) + \rho_i \Delta''(\rho_i) < 0$ to ensure concavity of the firms' problem, and ii) corner solutions can be excluded.[13]

4.1 Equilibrium and Welfare Analysis

Under separation firm i's expected profits are

$$\begin{aligned} \pi^S(\rho_i) &= \rho_i(v - \overline{u} + \Delta(\rho_i))L/2 + (1-\rho_i)(v-\overline{u})L/2 \\ &= (v - \overline{u} + \rho_i \Delta(\rho_i))L/2. \end{aligned}$$

The firm appropriates all returns from innovation and chooses the risk-return profile that maximizes expected innovation size, $\rho\Delta(\rho)$. The equilibrium probability of success is therefore given by

$$\Delta(\rho^{S,*}) + \rho^{S,*}\Delta'(\rho^{S,*}) = 0. \tag{11}$$

Under agglomeration, the firm choosing the higher risk aims for the higher innovation step, and in case both firms are successful, that firm wins over the labor pool. Thus any firm i's expected profit can be written as

$$\pi_i^A(\rho_i, \rho_j) = \rho_i(1-\rho_j)\Delta(\rho_i)L + \begin{cases} \rho_i\rho_j(\Delta(\rho_i) - \Delta(\rho_j))L & \text{if } \rho_i \leq \rho_j, \\ 0 & \text{otherwise.} \end{cases}$$

Consider two firms with $\rho_i \geq \rho_j$. Solving for the first-order condition of firm i we get

$$\Delta(\rho_i^{A,*}) + \rho_i^{A,*}\Delta'(\rho_i^{A,*}) = 0, \tag{12}$$

[13] Define $\widehat{\rho}$ as the unique solution to $\Delta(\rho) + \rho\Delta'(\rho) = 0$. Then, the following two conditions are necessary and sufficient to exclude corner solutions: i) $\Delta(\overline{\rho}) + \overline{\rho}\Delta'(\overline{\rho}) < 0$, and ii) $\Delta(\underline{\rho}) + \underline{\rho}\Delta'(\underline{\rho}) - \widehat{\rho}\Delta(\widehat{\rho}) > 0$.

while firm j's first-order condition is

$$\Delta(\rho_j^{A,*}) + \rho_j^{A,*}\Delta'(\rho_j^{A,*}) - \rho_i^{A,*}\Delta(\rho_i^{A,*}) = 0. \tag{13}$$

The next proposition characterizes the R&D equilibrium under agglomeration.

Proposition 5 *Consider the equilibrium in R&D strategies* $(\rho_i^{A,*}, \rho_j^{A,*})$ *under agglomeration. There exists a generically unique pure-strategy Nash equilibrium with* $\rho_i^{A,*} > \rho_j^{A,*}$ *which satisfies the first-order conditions (12) and (13).*

Competition for workers under agglomeration thus induces the firms to choose R&D projects with strictly different technical risks. One of the firms, call it i, chooses a safer project with a lower innovation size and makes profits if it is successful but its rival is not. Its optimal R&D project is therefore the one that maximizes the expected innovation size. Firm j, on the other hand, chooses a project with a higher technical risk and a higher innovation size target. Although this project has a lower expected innovation size, this strategy is optimal since it relaxes labor market competition in two ways. It firstly reduces the probability that both firms are successful and compete away their profits from innovation. Secondly, lowering ρ_j increases the productivity advantage of firm j if both firms' R&D is successful. Observe that in equilibrium, the firm with the safer project earns higher expected profits.[14]

Turning to the first stage of the game, firms choose to agglomerate if

$$\pi_i^A(\rho_i^{A,*}, \rho_j^{A,*}) + \pi_j^A(\rho_i^{A,*}, \rho_j^{A,*}) \geq 2\pi^S(\rho^{S,*}).$$

The following proposition summarizes the firms' location choice.

Proposition 6 *Compare R&D decisions and expected profits from innovation under the two location choices:*
(i) $\rho_i^{A,*} = \rho^{S,*} \leq 1/2$ *is a sufficient condition for both firms to earn higher profits from R&D under agglomeration.*
(ii) If the expected equilibrium profits accruing from R&D are higher under agglomeration than under separation, there exists a unique level $\psi > 0$ *such that in equilibrium,* $v - \overline{u} < \psi$ *implies agglomeration, and* $v - \overline{u} > \psi$ *implies separation.*

Proposition 6 is in line with the previous result that firms tend to agglomerate when the profitability of the basic quality as well as the equilibrium probabilities of R&D success are

[14] Firm i with $\rho_i > \rho_j$ earns higher profits than firm j if $(1-\rho_j)\rho_i\Delta(\rho_i)L > \rho_j\Delta(\rho_j)L - \rho_i\rho_j\Delta(\rho_i)L$ or $\rho_i\Delta(\rho_i)L > \rho_j\Delta(\rho_j)L$. This inequality always holds in equilibrium because $\rho_i^{A,*}$ maximizes the expected innovation size and $\rho_j^{A,*} < \rho_i^{A,*}$.

low. This combination favors agglomeration, because it minimizes the rents that are competed away in the labor market.

Turning to the welfare analysis, we have that aggregate welfare under separation is equal to the sum of the firms' profits while welfare under agglomeration it is

$$W^A(\rho_i, \rho_j) = (v - \overline{u} + \rho_j \Delta(\rho_j) + \rho_i(1 - \rho_j)\Delta(\rho_i))L.$$

The following proposition compares equilibrium R&D choices with the welfare maximizing ones and characterizes the efficiency of location decisions.

Proposition 7 *Suppose that the welfare function is globally concave in ρ_i and ρ_j for $\rho_j \leq \rho_i$. Then*
(i) conditional upon locations, firms choose the welfare maximizing R&D projects,
(ii) welfare is maximized when firms agglomerate.

As in the earlier specification in Section 3, firms take the welfare maximizing R&D decisions both under agglomeration and separation, and welfare is higher under agglomeration. The welfare difference between agglomeration and separation can again be decomposed into a labor productivity and an R&D portfolio effect. While the labor productivity effect works as before, the R&D portfolio effect operates slightly differently in the present setup where firms face a R&D risk-return trade-off. To see this, suppose that both firms would choose $\rho^{S,*}$ under agglomeration. Consider now a slight increase in the risk taken by firm j, i.e. a reduction of ρ_j. Then, if successful, firm j's innovation will become larger, yet the expected size of its innovation will become smaller. Under separation this move would reduce welfare, as expected welfare is increasing in expected innovation size. However, under agglomeration it increases welfare. Consider the benefit and the cost of increasing risk taking by firm j. Whilst the benefit in case of R&D success is the same under agglomeration and separation (controlling for the labor productivity effect), the cost is lower under agglomeration. The reason is that if firm j is unsuccessful, which is more likely when firm j takes higher risk, firm i might be successful. If so, firm i can employ the workers productively, which reduces the welfare cost of firm j's failure. This explains why one of the firms should take more risk under agglomeration and also why agglomeration allows for a more efficient portfolio of R&D projects. The final example III illustrates the above arguments with a simple R&D project technology.

4.2 Example III: Linear Risk-Return Technology

Consider the following simple, linear R&D technology:

$$\Delta_i = \beta(1-\rho_i).$$

The parameter β measures firm i's capacity for R&D, by determining how much Δ_i decreases when ρ_i is increased marginally. Notice that the functional form is chosen such that $\Delta_i = 0$ for $\rho_i = 1$ for all β; so innovation is always a risky activity.

Suppose first that the firms have chosen separate locations in the first stage of the game. Solving the firms' problem, we obtain $\rho^{S,*} = 1/2$ which implies $\Delta^{S,*} = \beta/2$ and profits under separation of

$$\pi^S(\rho^{S,*}) = L(v - \overline{u} + \beta/4)/2.$$

Suppose instead that the firms have chosen agglomeration. Solving for the equilibrium in pure strategies yields

$$\rho_i^{*,A} = \frac{1}{2},\ \rho_j^{*,A} = \frac{3}{8}$$

The equilibrium profits under agglomeration are

$$\pi_i^A(\rho_i^{*,A}, \rho_j^{*,A}) = \frac{5L\beta}{32} \text{ and } \pi_j^A(\rho_i^{*,A}, \rho_j^{*,A}) = \frac{9L\beta}{64}.$$

Since $\rho_i^{*,A}$, $\rho_j^{*,A} \leq 1/2$, the firms earn higher expected profits from R&D under agglomeration than under separation. A high research capacity β therefore favors agglomeration whereas a high value of $v - \overline{u}$ as before favors separation. Firms choose the same location if and only if

$$\frac{1}{2}\pi_i^A(\rho_i^{*,A}, \rho_j^{*,A}) + \frac{1}{2}\pi_j^A(\rho_i^{*,A}, \rho_j^{*,A}) \geq \pi^S(\rho^{S,*}) \Leftrightarrow v - \overline{u} \leq 3\beta/64,$$

which reflects this trade-off.

The variance in the average quality as a function of the firms' R&D strategies can be written as

$$Var[q] = \frac{\beta^2}{4}[\rho_1(1-\rho_1)^3 + \rho_2(1-\rho_2)^3].$$

Plugging in the equilibrium risk choices, we find also in this example that the variance under agglomeration ($631\beta^2/16384 \simeq 0.0385\beta^2$) is strictly larger than the variance under separation ($\beta^2/32 \simeq 0.03125\beta^2$).

5 Conclusions

We have developed a model demonstrating some central trade-offs involved in the location decision of research intensive firms. A joint location induces the formation of a large labor pool for firms to draw from. This allows a firm with a successful R&D project to expand its production more than under separate locations, which works as an agglomerative force. At the same time, however, wages increase via tougher competition for workers, which is a deglomerative force.

From our analysis it emerges that firms tend to agglomerate when the equilibrium probabilities of R&D success are low. This is, for instance, the case when it is very costly to increase the success probability. We have also developed three specific examples, from all of which we derive the empirical prediction that controlling for R&D costs there is a higher variance in average product quality (or, firm productivity) under agglomeration than under separation.

Turning to welfare, agglomeration leads to two distinct advantages compared to separation. First, all labor is put to its most productive use under agglomeration but not necessarily under separation. Second, firms choose a more efficient portfolio of R&D projects under agglomeration. Whence the first effect also arises in models of exogenous productivity shocks such as Krugman (1991a), the R&D portfolio effect results from the endogenization of firms' R&D strategy. The effect is novel to the literature on labor pooling and represents one of the main insights of the paper.

In our model firms always take the welfare maximizing R&D choices conditional upon location. Furthermore, as agglomeration in a cluster is welfare maximizing but not always the equilibrium outcome, the policy recommendation is to leave firms' R&D activities untouched, but to subsidize the formation of a cluster in situations where firms tend to stay apart; for instance in form of a tax break, or favorable land prices.[15] However, as usual, the welfare improving implementation of such a policy requires precise knowledge about the conditions under which such situations arise.

[15] Such policies are widely used. For instance, the French government announced recently a policy initiative aimed at supporting six globally competitive clusters and no less than 61 "poles of competitiveness" (The Financial Times, 13.07.05). The financial incentives available to these "poles" are 1.5bn EUR, and the policies include subsidies to infrastructure investments but also R&D subsidies.

Appendix

Proof of Proposition 2

(i) Consider first a symmetric equilibrium where $\phi_j^{A,*} = \phi_i^{A,*} = \phi^{A,*}$. Define:

$$\begin{aligned} \omega_1(\phi_i, \phi^{A,*}) &\equiv \partial \pi_i^A(\phi_i, \phi^{A,*})/\partial \phi_i \text{ for } \phi_i < \phi^{A,*}, \\ \omega_2(\phi_i, \phi^{A,*}) &\equiv \partial \pi_i^A(\phi_i, \phi^{A,*})/\partial \phi_i \text{ for } \phi_i > \phi^{A,*}. \end{aligned}$$

In equilibrium the following necessary conditions need to be satisfied:

$$\begin{aligned} \omega_1(\phi_i, \phi^{A,*}) &\geq 0 \text{ for } \phi_i \to (\phi^{A,*})_- \text{ and} \\ \omega_2(\phi_i, \phi^{A,*}) &\leq 0 \text{ for } \phi_i \to (\phi^{A,*})_+. \end{aligned}$$

These conditions ensure that $\phi_i^{A,*} = \phi^{A,*}$ is a local maximum for $\phi_j^{A,*} = \phi^{A,*}$. We have that

$$\begin{aligned} &\lim_{\phi_i \to (\phi^{A,*})_-} [\omega_1(\phi_i^{A,*}, \phi^{A,*})] - \lim_{\phi_i \to (\phi^{A,*})_+} [\omega_2(\phi_i^{A,*} \phi^{A,*})] \\ &\qquad = -\rho(\phi^{A,*})^2 \Delta'(\phi^{A,*}). \end{aligned}$$

Therefore, there is no symmetric equilibrium if $\Delta'(\phi^{A,*}) > 0$. Suppose instead that $\Delta'(\phi^{A,*}) = 0$. The first-order derivative of $\pi_i^A(\phi_i, \phi_j)$ is then continuous at $\phi_i^{A,*} = \phi^{A,*}$, which implies that $\pi_i^A(\phi_i, \phi^{A,*})$ is globally concave in ϕ_i. For $\Delta'(\phi^{A,*}) = 0$ the first-order condition (7) is thus both a necessary and a sufficient condition for a symmetric equilibrium in pure strategies to exist.

(ii) Consider now asymmetric equilibria where $\phi_i^{A,*} < \phi_j^{A,*}$. The first-order conditions (5) and (6) are necessary for an equilibrium to exist. We need to establish that if there exist $(\phi_i^{A,*}, \phi_j^{A,*})$ satisfying the first-order conditions, there exist no profitable deviations for the two firms. Consider firm i. Since the profit function of firm i is concave for $\phi_i \leq \phi_j^{A,*}$ and (5) is satisfied, there exists no profitable deviation to $\phi_i \leq \phi_j^{A,*}$. Instead consider a deviation to $\phi_i > \phi_j^{A,*}$. From symmetry follows that

$$\partial \pi_j^A(\phi_i, \phi_j)/\partial \phi_j \mid_{(\phi_i,\phi_j)=(\phi_i^{A,*},\phi_j^{A,*})} = \partial \pi_i^A(\phi_i, \phi_j)/\partial \phi_i \mid_{(\phi_i,\phi_j)=(\phi_j^{A,*},\phi_i^{A,*})} = 0.$$

Since $\pi_i^A(\phi_i, \phi_j)$ is concave for $\phi_i > \phi_j$, this implies that

$$\partial \pi_i^A(\phi_i, \phi_j)/\partial \phi_i \mid_{(\phi_i,\phi_j)=(\phi_j^{A,*}+\varepsilon,\phi_i^{A,*})} \leq 0$$

for all $\varepsilon > 0$. Finally, as $\partial^2 \pi_i^A(\phi_i, \phi_j)/\partial \phi_i \partial \phi_j < 0$, we have that

$$\partial \pi_i^A(\phi_i, \phi_j)/\partial \phi_i^A < 0 \ \mid_{(\phi_i,\phi_j)=(\phi_j^{A,*}+\varepsilon,\phi_j^{A,*})} \ \forall \varepsilon > 0.$$

Continuity of $\pi_i^A(\phi_i, \phi_j)$ then implies that there exists no profitable deviation to $\phi_i > \phi_j^{A,*}$. A similar argument establishes that firm j neither has an incentive to deviate.

Existence and uniqueness of this equilibrium is established in the proof of Part (i) of Proposition 4.

Proof of Proposition 3

(i) In a symmetric equilibrium the first-order conditions (5) and (6) collapse into (7). It follows directly from a comparison of (4) and (7) that $\phi^{A,*} \geq \phi^{S,*}$ if and only if $\rho(\phi^{A,*}) \leq 1/2$. The profits from R&D investment are $\rho(\phi^{S,*})\Delta(\phi^{S,*})L/2 - g(\phi^{S,*})$ under separation and $\pi_i^A(\phi^{A,*}, \phi^{A,*})$ under agglomeration. Using $\phi^{A,*} \geq \phi^{S,*}$, it follows that the profits from R&D investment are highest under agglomeration for $\rho(\phi^{A,*}) \leq 1/2$ as

$$\rho(\phi^{S,*})\Delta(\phi^{S,*})L/2 - g(\phi^{S,*}) \leq \pi_i^A(\phi^{S,*}, \phi^{A,*}) \leq \pi_i^A(\phi^{A,*}, \phi^{A,*}).$$

A similar argument establishes that profits from innovation are highest under separation for $\rho(\phi^{A,*}) > 1/2$.

(ii) It follows directly from a comparison of the first-order conditions (4) and (5) that $\phi_i^{A,*} \geq \phi^{S,*}$ if and only if $\rho(\phi_j^{A,*}) \leq 1/2$. Since $\phi_i^{A,*} = \phi^{S,*}$ if $\rho(\phi_j^{A,*}) = 1/2$, we have that

$$\rho(\phi^{S,*})\Delta(\phi^{S,*})L/2 - g(\phi^{S,*}) = \pi_i^A(\phi_i^{A,*}, \phi_j^{A,*}).$$

The fact that firm j earns higher equilibrium profits than firm i and $\partial\pi_i^A(\phi_i, \phi_j)/\partial\rho(\phi_j) = -\rho(\phi_i)\Delta(\phi_i)L < 0$ imply that

$$\rho(\phi^{S,*})\Delta(\phi^{S,*})L/2 - g(\phi^{S,*}) \leq \pi_i^A(\phi_i^{A,*}, \phi_j^{A,*}) < \pi_j^A(\phi_i^{A,*}, \phi_j^{A,*})$$

if and only if $\rho(\phi_j^{A,*}) \leq 1/2$.

(iii) Reformulating the profits under separation shows that $v - \overline{u}$ merely shifts profits, and bears no impact on the determination of ϕ_i. Hence a unique level of $v - \overline{u}$ exists above which separation is preferred. Moreover, this level of $v - \overline{u}$ is strictly positive if both firms invest more and the expected profits from their investments in R&D are higher under agglomeration, which the conditions of statement (i) and (ii) of this proposition ensure.

Proof of Proposition 4

(i) To ensure a strictly globally concave welfare function we assume throughout our analysis that

$$(i)\ W_{ii}, W_{jj} < 0,$$
$$(ii)\ W_{ii}W_{jj} - W_{ij}W_{ji} > 0,$$

where $W_{ij} = \partial^2 W/\partial\phi_i \partial\phi_j$. As can be easily checked, both conditions are satisfied if $g(\cdot)$ is sufficiently convex.

The equilibrium and the welfare maximizing R&D investments solve the same first-order conditions, (5) and (6). Since the welfare function is globally concave under the assumption that $g(\cdot)$ is sufficiently convex, there exists a unique $(\phi_i^{A,*}, \phi_j^{A,*})$ that solves the first-order conditions (modulo firm symmetry). Hence, we can also conclude that there exists one and only one pair that solves the equilibrium conditions of Proposition 2.

(ii) We have that

$$W^S(\phi^{S,*}, \phi^{S,*}) \leq W^A(\phi^{S,*}, \phi^{S,*}) \leq W^A(\phi_i^{A,*}, \phi_j^{A,*})$$

where the first inequality follows from the welfare analysis of the benchmark model presented in section 2. This proves the second part of the proposition.

Proof of Proposition 5

Since $\rho_i^{A,*}$ is independent of $\rho_j^{A,*}$, it follows from concavity plus the additional assumptions made on the curvature of the profit function that there exists a unique and interior solution to (12), $\rho_i^{A,*}$. Given $\rho_i^{A,*}$, the same assumptions ensure a unique and interior best-response of firm j, $\rho_j^{A,*}$. Therefore, there exists a unique solution to the first-order conditions (12) and (13) (modulo firm symmetry). It remains to be shown that the firms do not want to deviate from $(\rho_i^{A,*}, \rho_j^{A,*})$. Consider firm i. We have that $\partial\pi_i/\partial\rho_i \to (\rho_j^{A,*})^2\Delta'(\rho_j^{A,*}) > 0$ for $\rho_i \to (\rho_j^{A,*})_-$ and $\partial\pi_i/\partial\rho_i \to \Delta(\rho_j^{A,*}) + \rho_j^{A,*}\Delta'(\rho_j^{A,*}) > 0$ for $\rho_i \to (\rho_j^{A,*})_+$. Since the profit function is concave in ρ_i for $\rho_i < \rho_j^{A,*}$ and for $\rho_i > \rho_j^{A,*}$ as well as continuous at $\rho_i = \rho_j^{A,*}$, we have that $\rho_i^{A,*}$ is a global maximum. A similar argument establishes that firm j neither has an incentive to deviate.

Proof of Proposition 6

(i) Suppose that $\rho_i^{A,*} = \rho_j^{A,*} = \rho^{S,*} \leq 1/2$. Then, the profits that accrue from R&D under agglomeration are no less than under separation as $\rho^{S,*}(1-\rho^{S,*})\Delta(\rho^{S,*})L \geq \rho^{S,*}\Delta(\rho^{S,*})L/2$. In equilibrium, $\rho_j^{A,*} < \rho_i^{A,*} = \rho^{S,*} \leq 1/2$. Therefore, firm i earns strictly higher profits from R&D under agglomeration. A revealed preference argument establishes that firm j earns no less from R&D under agglomeration.

(ii) Identical to the proof of Proposition 3 (iii).

Proof of Proposition 7

(i) The first-order conditions characterizing the welfare maximizing R&D hazard rates are identical to (12) and (13). Therefore, the firms choose the welfare maximizing R&D projects in equilibrium.
(ii) The only thing left to show is that welfare is maximized when firms agglomerate. This holds as $W^S(\rho^{S,*}, \rho^{S,*}) \leq W^A(\rho^{S,*}, \rho^{S,*}) \leq W^A(\rho_i^{A,*}, \rho_j^{A,*})$ where the first inequality follows from the welfare analysis of the baseline model.

References

Acs, Z. J, D. B. Audretsch, and M. P. Feldman (1994): R&D Spillovers and Recipient Firm Size, Review of Economics and Statistics, 76, 336-340.

Almeida, P and B. Kogut (1999): The Exploration of Technological Diversity and Geographical Localization in Innovation, in Acs, Z. J and B. Yeung (ed's): Small and Medium-sized Enterprises in the Global Economy, 103-20, Ann Arbor: University of Michigan Press.

Audretsch, D.B. (1998): Agglomeration and the Location of Economic Activity, CEPR Discussion Paper Series (Industrial Organization), No. 1974.

Audretsch, D.B. and M.P. Feldman (1995): Innovative Clusters and the Industry Life Cycle, CEPR Discussion Paper Series (Industrial Organization), No. 1161.

Audretsch, D.B. and M.P. Feldman (1996): R&D-Spillovers and the Geography of Innovation and Production, American Economic Review, 86, 630 - 640.

Audretsch, D.B. and M.P. Feldman (2004): Knowledge Spillovers and the Geography of Innovation, in Henderson, J.V., and J. F. Thisse (ed's): Handbook of Regional and Urban Economics, vol. 4, Amsterdam: Elsevier, 2714-2739.

Bhattacharya, S. and D. Mookherjee (1986): Portfolio Choice in Research and Development, RAND Journal of Economics, 17, 594-605.

Baumgardner, J.R. (1988): The Division of Labor, Local Markets, and Worker Organization, Journal of Political Economy, 96, 509-527.

Combes, P.-P. and G. Duranton (2005): Labour Pooling, Labour Poaching, and Spatial Clustering, forthcoming in Regional Science and Urban Economics.

Dasgupta, P. and E. Maskin (1987): The Simple Economics of Research Portfolios, The Economic Journal, 97, 581-595.

Duranton, G. and D. Puga (2004): Microfoundations of Urban Agglomeration Economies, in Henderson, J.V., and J. F. Thisse (ed's): Handbook of Regional and Urban Economics, vol. 4, Amsterdam: Elsevier, 2063-2117.

Fosfuri, A. and T. Rønde (2004): High-tech Clusters, Technology Spillovers, and Trade Secret Laws, International Journal of Industrial Organization, 22, 45-65.

Grossman, G. M. and E. Helpman (1991): Quality Ladders in the Theory of Growth, Review of Economic Studies, 58, 43-61.

Jaffe, A., M. Trajtenberg and R. Henderson (1993): Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations, Quarterly Journal of Economics, 108, 577-598.

Krugman, P. R. (1991a): Geography and Trade, Cambridge, Massachusetts: The MIT Press.

Krugman, P. R. (1991b): Increasing Returns and Economic Geography, Journal of Political Economy, 99, 484-99.

Marshall, A. (1920): Principles of Economics, 8th edition, London, England: MacMillan.

Picard, P. and E. Toulemonde (2000): The Emergence and Persistence of Regional Asymmetries under Minimum Wages, University of Manchester, mimeo.

Rosenthal, S. and W. Strange (2001): The Determinants of Agglomeration, Journal of Urban Economics, 50, 191-229.

Saint-Paul, G. (2003): Information Sharing and Cumulative Innovation in Business Networks, CEPR Discussion Paper Series (International Macroeconomcis), No. 4116.

Stigler, G. (1951): The division of labour is limited by the extent of the market, Journal of Political Economy, 59, 185-193.

Stahl, K. and U. Walz (2001): Will there be a concentration of alikes? The impact of labor market structure on industry mix in the presence of product market shocks, Working paper 140, Hamburg Institute of International Economics.

Topel, R. H. (1986): Local Labor Markets, Journal of Political Economy, 94, 1111-1143.