BANCA D'ITALIA
EUROSISTEMA

Temi di discussione

(Working papers)

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April 2008

Number 667

INNOVATION DRIVEN SECTORAL SHOCKS AND AGGREGATE CITY CYCLES

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Abstract

This paper formalizes a mechanism through which diversification in the production of research and development across firms located in a city dampens volatility in the local labor market, improves the incentives to perform research and development and smooths the aggregate business cycle fluctuations of a city. This is done by adapting the standard multisector quality ladder model (Grossman and Helpman, 1991) in order to allow for heterogeneity across firms, thus taking into account knowledge spillovers across heterogenous sectors, knowledge accumulation, pecuniary externalities and segmented labor markets. As a result, according to the local degree of diversification in research and development, sectoral technological shocks have an influence on the current choice of research and development and the location of production, and in turn on local business cycles and the life cycle of the city: diversification in research & development allows innovations in different sectors of the city to arrive at different points in time, thus avoiding to put pressure on the local labor markets and keeping wage discipline. This permits firms located in the city to perform enough research and development and possibly beat outside competition in discovering and manufacturing new products, thus growing (at the aggregate city level) through less volatile cycles.

JEL Classification: E32, O31, R23.
Keywords: quality ladder with heterogeneity across firms, labor pooling economies, knowledge spillovers, diversification, Schumpeterian growth in the city.

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Contents

1 Introduction[1]

Economic literature is replete with anecdotal evidence of the link between diversification in production and volatility of the business cycle of a city. The latter would in turn have an influence on the life cycle of the city: Brezis and Krugman (1997) refer to Bairoch (1985) to make clear how the product life cycle may drive the life cycle of cities: "Old cities that remain locked into traditional industries are shouldered aside by upstart cities that embody the new. In time, of course, these upstarts are themselves often shouldered aside by yet newer urban centers". Another quotation from the same authors makes a very important point relevant to the present paper: "In some cases, cities —not huge cities like London and Paris, but smaller cities with narrower export bases— appear to go through a life cycle of growth and decay". These quotes stress that while cities go through booms and slumps of their life cycles depending on the life cycle of their primal productions, larger and more diversified cities seem to be able to avoid these unfortunate twists of fate. Krugman (1991) provides several examples of cities in the United States which have gone through very severe recessions as their primal production became obsolete: carpets in Dalton, tyres in Akron, the automotive industry in Detroit, and the steel industry in Pittsburgh. Sometimes recessions have brought cities to (or close to) disappearance, while other cities have managed to survive and find some sort of resurrection. Analogous cases have occurred in Europe as well (Glasgow, Liverpool, Manchester, Liege, Genoa, Taranto).

Anecdotal evidence aside, the empirical literature has also stressed the importance of the link between sectoral shocks, industry displacement and employment volatility at the city level in the US (Coulson, 1999; Carlino, DeFina and Sill, 2001).

These two pieces of evidence —that is the observed link between diversification and smoothed fluctuations (fact 1) and the link between sectoral shocks, industry displacement and employment volatility (fact 2)— convey the idea that industry specific technological shocks trigger local industry specific fluctuations. These fluctuations occur through displacement of industries across locations (and countries) and imply volatility in local labor markets. The same industry specific fluctuations build up in aggregate business cycles at the city level, and the way they do crucially depends on the diversification of activities within the city: more diversified cities enjoy steadier growth paths and less pronounced business cycles.

Another two pieces of evidence motivate this paper. The first one is that, in the real world, research & development (henceforth R&D) intensities differ widely across industries with R&D heavily concentrated in a few sectors of the economy (fact 3). This evidence is hard to conciliate with the standard quality ladders model, where R&D effort is uniform across industries, since demand for goods, production costs, and profits do not differ across industries, and investing in R&D in any sector gives the same expected return. In the same class of models, moreover, any co-movement of innovation processes across industry is precluded, since innovation processes are independent and identically distributed across industries. The second piece of evidence is provided by the debate on the effect on wages and employment in developed countries of trade with labor abundant low wage developing countries (fact 4, Lawrence and Slaughter, 1993; Sachs

[1] I am grateful to Antonio Accetturo, Fabio Busetti, Giuseppe Carollo and Juri Marcucci, seminar participants at NARSC 2007 (Savannah) and two referees from *Temi di discussione* for their comments. I am indebted to Vincenzo Galasso, Marjorie Gassner, Michael Haliassos, Elhanan Helpman, Gianmarco Ottaviano, Dani Tsiddon, Philippe Weil, Oved Yosha and seminar participants at Alghero, Buenos Aires, Bar Ilan, Pittsburgh, Roma (Ente Einaudi), Salerno (CSEF) for providing comments on an earlier version, circulated with the title "Death and birth of a city: The myth of the (Arabian) phoenix". All remaining errors are mine. The views expressed herein are those of the author and not necessarily those of Bank of Italy.

and Shatz, 1994; Dewatripont, Sapir, Sekkat, Guazzarotti and Lamorgese, 1998). Such debate – originated in the early 90's by the rise of Asian tigers and recently revived by China and India's steady growth – hinged upon the threat of job losses and increasing wage gaps between skilled and unskilled workers in developed countries due to international competition by developing countries, characterized by abundance of low paid workers. Such a fear might be rationalized on the grounds that developed countries might be unable to find a shelter from competition by climbing the quality ladder, either because it might be too expensive to make it worthwhile, or because international competitors might climb the ladder as well.

This paper formalizes one mechanism which provides a theoretical background to these four pieces of evidence, based on the effect of diversification across firms and sectors in the production of R&D. In a nutshell, innovation by a firm in a certain sector is a random variable distributed according to a multivariate poisson process, whose arrival rate —i.e. the instantaneous probability of innovation— depends on firm-sector specific employment in R&D and a firm-sector specific spillover from a common stock of knowledge. The lower the dispersion across firms and sectors in the city of the distribution of the spillover, the smaller the diversification in R&D and the more likely the event that more firms located in the city and active in different sectors innovate at the same time. If this happens, larger current production in the sectors where innovation has occurred comes at the cost of higher labor costs for R&D, less employment in research and a lower probability of innovation in the future, lower competitiveness of a city's products in the international markets, possible relocation of production out of the city and larger fluctuations in both city's aggregate business cycles and local labor market. The mechanism through which all this action occurs is the well known negative intertemporal spillover which characterizes all quality ladder models, although, in the present setting, its amplitude is made explicitly dependent on diversification of R&D technology.

Technically the model adapts the standard multi-sector quality ladder model (Grossman and Helpman, 1991; Aghion and Howitt, 1998) introducing three novelties. First, knowledge is allowed to spread across sectors (borrowing from Romer, 1986). In the setting of this model this buys the possibility of observing correlated innovation processes while preserving heterogeneity across sectors (fact 3), and delivers an inverse relation between correlation in innovation processes and diversification in R&D technology, and a formal link between such correlation, local growth and local cycles (fact 1). Second, R&D technology is a concave function of R&D employment. This implies that if production is displaced as a consequence of international competition and workers are released, they might be not immediately reabsorbed in R&D, thus determining a relation between correlation among innovation processes and volatility in the local labor market (fact 2). Higher diversification and lower correlation go along with lower volatility, thus formally representing Marshall's labor pooling economies.[2] Third, labor markets are internationally segmented, which allows the modeling of interaction with the labor abundant South (fact 4). In the set-up of this model this implies that profits cease to be a constant mark-up on local labor costs, and firms can forfeit their profits if correlated innovations impose a too harsh wage pressure; at the same time expenditure becomes an endogenous variable and pecuniary externalities arise, since higher wages command higher expenditure and higher production, thus exacerbating the trade-off between (absence of) diversification and labor market volatility.

While nothing prevents using this model as a tool to analyze the link between product cycles

[2]In so doing this paper provides a simple theoretical example of the operating of Marshall's (1920) labor pooling externalities in a growth model. Fujita and Ogawa (1982) and Hesley and Strange (1990) also provide a formalization of such a kind of agglomeration economies, but they rather do it in a context of urban models in order to analyze the spatial configuration of the city.

and aggregate business cycles in larger agglomeration —such as regions and countries, the focus on the city is more natural for two reasons. First, the link between average correlation among innovation processes across sectors and diversification in R&D technology rests on the existence of external economies and knowledge spillovers, whose diffusion is thought as locally bounded (Rosenthal and Strange, 2004). Second, the whole mechanism in the paper plays on the absence of diversification, and even large cities are far more specialized than the smallest nations (Brezis and Krugman, 1997).

The structure of the paper is as follows: section 2 contrasts the modeling choices taken in this paper with previous literature. Section 3 builds the basic set up of the model. Section 4 obtains the equilibrium, while section 5 defines diversification within the city, and investigates the mechanism through which diversification dampens the volatility of the equilibrium employment in the city. Section 6 enables the basic set up to take into account two issues, namely learning by doing and labor force heterogeneity. Section 7 wraps up the results of the paper and concludes.

2 The literature

In order to formalize the mechanism which generates diversification in the city and its linkages with volatility in city growth and employment, this paper blends elements of growth theory, business cycle theory, patent races, factor models, and risk-sharing in an original way. Leaving aside the above mentioned innovations with respect to the standard quality ladder model, the next paragraphs acknowledge similarities and differences with previous literature.

This paper considers the link between diversification in R&D and local labor market fluctuations, which is a novelty with respect to the vast literature that has looked at the link between sectoral diversification in production and volatility in local business cycle, in local labor markets and in the city's life cycle.[3] This literature starts with Brezis and Krugman (1997), who analyze cases where mature products tend to locate in established cities, while upstart products locate in small and undiversified ones. The economic mechanism underlying such evolution is that producers of established products improve their products relying on cross-sector knowledge spillovers, so they value large and diversified cities and are able to sustain larger wage and rent costs which are typical of those cities. New products springing from path-breaking innovations, instead, develop in small and undiversified urban centers, since they do not enjoy significant spillovers from the bulk of old knowledge concentrated in large cities featuring larger crowding costs.

Duranton and Puga (2001) analyze the relation between diversity of the sectoral composition of research in the city and innovation, pointing out that since innovation goes through a costly process of trials and errors which takes advantage of diversification, while production of the innovated products is favored by specialization, diversified and specialized cities coexist in equilibrium, and there is a link between diversification and the life cycle of products. Such a result is also achieved in this paper, through cross sector knowledge spillovers and probabilities of improving upon the state of art quality which are heterogenous across sectors.

Duranton (2007) uses a rather standard quality ladder model to study innovation driven displacement of industries across cities and confronts the predictions of such a model to the city size distribution of the USA and France. Although his model also takes into account the fact

[3]Notice that although diversification in R&D and production are two distinct concepts, the latter is implied by the former in the class of quality ladder models with drastic innovation —i.e. where the "winner" of the innovation race "takes all" and serves the whole market.

that the probability of innovation in one industry enjoys spillover from R&D effort in different industries, it does not exploit the heterogeneity across industries. He also assumes that labor is mobile across cities, thus preventing the analysis of the effect of wage pressure on local R&D, and assumes some degree of inertia in the transfer of R&D knowledge across locations.[4] As in Duranton (2007, section V), the basic set-up of the present model also contemplates the trade-off between agglomeration economies —introduced by the spillover in R&D activities— and crowding costs –represented by the general equilibrium effect in the labor market.

An example of models where cross-industries diversification in R&D technology is allowed is Scott Taylor (1993), but unlike the present paper, his innovation processes are independent and identically distributed across sectors and there are no cross-sectors spillovers.

The interaction among sectors in the city, that in the present paper is achieved through competition in the labor market, has been recently analyzed by Dinopoulos and Segerstrom (2006), in a different context, in which the outside world (the South in the authors' notation) can imitate innovations achieved in the city (the North) but never innovates.

Finally, the factor structure outlined in section 3.4 is close in spirit to the one used in Ballester, Calvó-Armengol and Zenou (2006) to analyze networks among agents, as well as to the one used in Forni and Reichlin (2001) to analyze the scope of risk-sharing among EU regions and US states.

3 The basic set up

3.1 Quality ladders

I consider an economy with a continuum of industries indexed by $j \in [0, 1]$. In each industry the good can be produced in an infinity of different qualities, indexed by m, where m is an integer. Each different quality provides a different flow of consumption services ($q_m(j)$), and each new quality embodies a leap of $\lambda > 1$ upon the previous quality. Hence, $q_m(j) = \lambda q_{m-1}(j)$ for each m, j. To discover the new quality entrepreneurs have to engage into an R&D race which is characterized later on (section 3.4).

3.2 Preferences and demand

The economy is populated by a unit continuum of households. Each household lives only one period, supplies her labor in exchange for wage (w), and enjoys utility outpouring from consumption and leisure.[5] Marginal disutility to work (or utility coming from leisure) is constant and equal to a. Consumers evaluate all qualities of all consumption goods according to the following utility function

$$U_t = \log D(t) - al \tag{1}$$

[4]Technically he assumes that "quality improvement in an industry requires the knowledge associated with the leading quality. In turn this knowledge is available only to research firms located in the same city as the industry leader".

[5]I assume the worker to be short-lived because I want to condition out the intertemporal choice of consumption and expectations about future stochastic income. In such a way I completely cut off consumption smoothing through saving/dissaving, and I focus solely on income/consumption smoothing via the choice of settlement. Alternatively, a myopic consumer only evaluating current consumption or non storable income would do the job. But I do not consider these latter hypotheses to be more realistic than the one I have adopted here.

where l is the fraction of the time endowment spent working (limited from above by $\bar{L}$), and $D(t)$ is a composite good defined as

$$\log D(t) = \int_0^1 \log \big[\sum_m q_m(j) x_{mt}(j)\big] dj. \tag{2}$$

This definition of consumers' preferences delivers that *i)* consumption goods are substitutes with unit elasticity of substitution, and that *ii)* qualities of the same consumption good are perfect substitutes, maintaining that better qualities provide higher utility and are therefore preferred.[6]

Each cohort of consumers at time t exchanges labor services for wages. Labor is homogeneous: a worker can indifferently work in the productive or in the research department of a firm, and she receives the same wage. Since labor market is assumed to be perfectly competitive, any wage difference would be arbitrated away. The budget constraint is therefore

$$E_t = \int_0^1 \big[p_{mt}(j) x_{mt}(j)\big] dj \leq w_t, \tag{3}$$

where w_t is the wage paid to both researchers and manufacturing workers. Since all qualities are perfect substitutes, only the quality carrying the lowest quality adjusted price (call it $\tilde{m}$) is demanded at the optimum. Since all goods are weighted in the same way, expenditure does not change across goods, and the consumer spreads expenditure evenly across all goods. Individual demand for each good is then

$$x_{mt}(j) = \begin{cases} E_t/p_{mt}(j) & \text{for } m = \tilde{m}_t(j) \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

Finally, at the optimum each household supplies one unit of labor, provided that the real wage is not smaller than the marginal disutility to work.[7]

3.3 Production

I will assume the following simplifying hypotheses: *i)* the economy is constituted by only two locations, one city and the outside world,[8] and *ii)* the outside world is modeled as a unique location competing against the entrepreneurs both on the grounds of discovering a new quality of the final good and of selling it to consumers.

In each location a unit continuum of industries is represented (indexed according to the good produced). In each industry in each location a unit continuum of entrepreneurs is located, indexed by $i \in [0, 1]$. All entrepreneurs perform R&D to discover a new quality of the good produced in the industry. Once discovered, the new quality is uniquely produced by its inventor, who stops performing R&D because of the "replacement effect" (Grossman and Helpman, 1991; Reinganum, 1983). In each industry firms (or entrepreneurs) compete on price (against both other local entrepreneurs and the outside world). Each firm can produce any quality except the

[6] Notice that leisure is not a substitute for any of the consumption goods.

[7] The condition is $w_t/[p(t)D(t)] \geq a$ where $p(t)$ is a price index for the composite good. Let $\underline{\underline{w}}$ be the minimum wage for which this condition holds.

[8] Ideally one should consider several different locations in the economy, and model symmetrically the way external demand is formed. Here I decided to keep the model simple and ignored this issue, since the economy being considered is spaceless and third country effects do not play any crucial role (Behrens, Lamorgese, Ottaviano and Tabuchi, 2005; Behrens, Lamorgese, Ottaviano and Tabuchi, 2007).

state of art, which is only produced by the inventor.[9] One unit of labor allows to produce one unit of any quality of any consumption good.[10]

Since j is just a label for the industry, one can sort the industries such that $\beta \in [0,1]$ is the mass of products manufactured in the city, and $1-\beta$ is the mass of products produced outside the city.

Competition drives the price of a unit of the previous quality down to the marginal cost of the cheapest competitor $w = w_0$.[11] The producer of the state of the art quality provides a product λ times as good as the previous quality and imposes a price up to λ times as large as the marginal cost. Given the shape of the demand function (4) and consumer preferences, the leader does not impose any price higher than λw_0, because demand, sales and profits would be nil. Similarly she does not lower the price discretely under λw_0 because given the unit price elasticity of (4), she would not reap any additional revenue by so doing. But total labor compensation would be larger and the leader would make smaller operative profits. The leader's optimal response to the follower imposing a price w_0 is therefore to set a price a shade below λw_0 and serve the whole market given constant returns to scale in production.

On the other hand the follower's optimal response to the leader setting the price equal to λw_0 is to impose price equal to w_0. In fact for any price $p_F \geq w_0$ s/he reaps zero profits, for any $p_F < w_0$ s/he makes operating losses.[12] Making null profits drives the followers out of the market.

Summarizing, equilibrium prices, quantities and profits are:[13]

$$p_L(j) = \lambda w_0,\ p_F = w_0,\ x_L(j) = X_{\tilde{m}},\ x_F(j) = 0 \tag{5}$$

$$\Pi_L(j) = \big(\lambda w_0 - w\big) X_{\tilde{m}},\ \Pi_F(j) = 0, \tag{6}$$

where $X_{\tilde{m}}(j)$ is the world aggregate demand accruing to the producer of good j in the city. Since the top quality of the good in all sectors j receive the same amount of expenditure, $X_{\tilde{m}}(j) = X_{\tilde{m}}$ and $\Pi(j) = \Pi$ for all j.

3.4 R&D: the technological race

Firms compete for technological leadership against other firms within the same sector and against the outside world. Technological leadership grants temporary monopoly rents. They are temporary since, due to the random process of innovation, the time during which the leader reaps the rent is also a random variable, and obsolescence and leapfrogging are granted. This is what this literature means by creative destruction.

[9] Due to the use of a memoryless poisson R&D technology and total disclosure of the patent, which are standard hypotheses in this literature (Grossman and Helpman, 1991; Aghion and Howitt, 1998), each researcher finds it more convenient to build upon someone else's invention rather than try to imitate and produce the same quality. The former strategy is rewarded with expected monopolistic gains while the latter just delivers zero profits (Nash-Bertrand price competition) for both incumbent and imitator.

[10] Assuming the slope of the linear production function to be different from 1 does not change the results.

[11] I assume that labor is not a scarce resource outside the city, so that the wage paid outside the city is $\underline{w}^F$. In order to guarantee the existence of the equilibrium, it is useful to call $\underline{w}^H$ the wage level at which demand for workers in R&D exceeds the number of workers in the city, and let $w_0 = \min\{\underline{w}^H, \underline{w}^F\} > \underline{\underline{w}}$.

[12] In fact the equilibrium price level the follower sets is not unique. Any price higher than w_0 is still an equilibrium, in that the follower cannot improve her/his situation by deviating. Since any price higher than w_0 grants the same null profits, all these equilibria are pay-off equivalents and one can only focus on $p_F = w_0$.

[13] Notice that the wage paid to workers is not constrained to be the same across all locations. Shortage of labor may drive wages upward, which is exactly all what Marshall's (1920) local economies are about.

The outside world produces innovations in sector j according to a random process, namely a Poisson(ψ_j) with $j \in [0,1]$. Analogously, for firms within the city, innovation is a random event which occurs according to a Poisson law with arrival rate ι_{ij}. As usual in this setting the arrival rate is equal to the instantaneous probability of success: that is, a firm which exerts an effort ι_{ij} in research activity has a positive probability ι_{ij} of success at each point in time dt. In case of success the firm is able to produce the improved quality —which provides λ times as many consumption services as the previous quality, serves all the market, and reaps profits equal to Π_L until a new improved quality is invented.[14] With probability $1 - \iota_{ij}dt$ at each dt the firm does not achieve the innovation and its production, sales and profits stay equal to zero.

3.4.1 R&D technology, diversification in R&D and correlated innovation

In order to account for externalities in the R&D activity and correlation in the innovation processes, this paper departs from the standard quality ladder model. Along this endeavor it is convenient to suppose that research effort ι_{ij} is made of two different components

$$\iota_{ij} = \alpha_{ij}\iota + \xi_{ij}, \tag{7}$$

where ξ_{ij} is the idiosyncratic component of the research effort and $\alpha_{ij}\iota$ is the common component. The former depends on the number of researchers ϕ_{ij} employed by firm i in sector j through an increasing and concave function $\xi_{ij}(\ )$ which can be firm-specific, namely $\xi_{ij} = \xi_{ij}(\phi_{ij})$; the latter is the product of a firm-sector specific loading α_{ij} and a Romer's (1986) style common stock of knowledge, which is just a weighted average of idiosyncratic research efforts with weights ω_{ij}, namely $\iota = \int_i \int_j \omega_{ij}\ \ \xi_{ij} di dj$.[15]

The factor loadings α_{ij} give a measure of how much firm i in sector j of the city is able to take advantage of the common shock, and has a generic distribution $G(\alpha)$ over all firms in all sectors in the city.

This structure reflects the idea that innovation is partly due to the idiosyncratic R&D effort that one firm exerts, and partly to spillovers from other firms' own idiosyncratic research effort, which is a standard feature of endogenous growth models based on increasing returns external to the firm (Romer, 1986). Spillovers are due to the fact that idiosyncratic research effort exerted by a certain firm in a certain sector enters other firms' research effort through the common stock of knowledge.

This setting is very general in that it allows for a very complex structure of correlation of the innovation processes and, by specifying opportunely the weights ω_{ij}, for a decay of the knowledge spillover. For instance, research intensity in the cell ij could be due to a world common factor, a sector specific factor common to all cities, a city specific factor common to all sectors within the city, and a sector factor specific for the city; alternatively the city common factor might instead be a weighted average of the research intensity of all cities with weights strongly decreasing as the distance increases; even further, the sector common factor might be

[14] The period during which the leader reaps monopoly profits is random as well: waiting time for the next innovation is distributed according to a negative exponential of parameter $\iota_{ij} + \psi_j$, that is a $\Gamma(1, \iota_{ij} + \psi_j)$.

[15] Formally, innovation for firm i in sector j of the city is a random variable Z_{ij} obtained as the sum of a common component χ_{ij} and an idiosyncratic component z_{ij}. z_{ij} is a random variable distributed as a i.i.d. Poisson with arrival rate ξ_{ij}, while χ_{ij} is the product of a loading α_{ij} and a weighted average of i.i.d. poisson random variables, i.e. $F = \int_i \int_j \omega_{ij}\ \ z_{ij}(\phi_{ij}) di dj$ with weights ω_{ij}. By the properties of aggregation of i.i.d. poisson random variables, F is also distributed as a poisson with arrival rate $\iota = \int_i \int_j \omega_{ij}\ \ \xi_{ij} di dj$, while Z_{ij} is distributed as a multivariate poisson with arrival rate $\iota_{ij} = \alpha_{ij}\iota + \xi_{ij}$ (Johnson and Kots, 1969, page 298).

a weighted average of the research intensities of all other sectors with weights decreasing along the economic distance across sectors (measured according to some metrics, for instance the one in Conley and Dupor, 2003; Lamorgese and Ottaviano, 2007).

Since each entrepreneur can set up a research plant in any sector, because there is no fixed cost of setting up a research plant and there is only one type of labor, for the remainder of the paper it will be assumed that all firms in all sectors have the same idiosyncratic R&D technology $\xi_{ij}(\phi_{ij}) = \xi(\phi_{ij})$, whereas their optimal choice of employment in R&D may vary. It will also be assumed that the each firm's idiosyncratic R&D contributes equally to the common stock of knowledge, i.e. $\omega_{ij} = \omega$, and such contribution will be normalized to 1. Beyond a huge simplification of the algebra, such hypotheses are not needed for any of the results of the paper to hold.

The departure from standard quality ladders through the introduction of the factor structure in the innovation process and the knowledge spillover delivers the main result of the paper, that is it allows to obtain an explicit link between average correlation among innovations across firms in the city and the moments of the distribution $G(\alpha)$, which controls the amount of diversification in R&D technology. In particular, diversification for R&D technology described by equation (7) depends on the variance of the distribution $G(\alpha)$; diversification is minimal if $G(\alpha)$ is degenerate and $\alpha_{ij} = \alpha$, and maximal for $G(\alpha)$ uniform over a support $[\underline{\alpha}, \overline{\alpha}]$. In the latter case spillovers from the common stock of knowledge are are firm/sector specific, so diversification is maximal, while in the former case all firms in all sectors receive the same spillover, so diversification is minimal. Finally, the mean of $G(\alpha)$ controls the relative weight of the common and idiosyncratic components of the research effort: if the common component counts little because the mean of α_{ij} is small, on average a small variance of the distribution has a modest influence on diversification.[16] In section 5 I'll show that, at the equilibrium, increased average correlation in innovation delivers on average more innovation, a larger share of manufacturing goods (β) being produced in the city and a stronger wage pressure that discourages R&D, which jointly with random innovation creates fluctuations of the aggregate city business cycle.[17]

An informal analysis of sectoral comovement based on pairwise correlation among innovation in different sectors provides a nice intuition about the driving forces underlying the link between diversification and equilibrium R&D employment. The covariance among any pair of random variables Z_{ij} describing discovery of firm i in sector j is a function of the common stock of knowledge (ι) and the loadings of the two cells (sectors/firm) (α_{ij}) (Johnson and Kots, 1969, page 298),

$$cov(Z_{ij}, Z_{sn}) = \alpha_{ij} \;\; \alpha_{sn} \;\; \iota. \tag{8}$$

whereas correlation is given by

$$corr(Z_{ij}, Z_{sn}) = \frac{\alpha_{ij} \;\; \alpha_{sn} \;\; \iota}{(\alpha_{ij}^2 \;\; \iota + \xi_{ij})^{1/2} (\alpha_{sn}^2 \;\; \iota + \xi_{sn})^{1/2}} \tag{9}$$

[16] Diversification among discovery processes is also maximal in the standard quality ladder model, since random discovery processes are independent across sectors, hence there is zero correlation among discoveries, and contemporaneous innovation is an event with zero probability measure, i.e. it only happens by accident (Grossman and Helpman, 1991; Aghion and Howitt, 1998).

[17] However even in a standard quality ladder model without cross-sector spillovers in R&D technologies, upward wage pressure can be produced even if discovery processes are uncorrelated. Sequential innovation is enough: if at time t the share of sectors producing in the city is β and a firm innovates in another sector, without any of the existing sectors shutting down, β increases to β' and excess demand of labor drives wage up (Lamorgese, 2001).

Both pairwise covariance and pairwise correlation among innovations in firms belonging to two different sectors are increasing in the loadings of the common stock of knowledge.

However, the relevant notion of diversification in this setting is average correlation among all firms in all sectors in the city, which is a weighted average of (9) using the distribution of the α's as weighting scheme. I call this statistics $\overline{\rho}(Z)$. Appendix A3 shows that, using the Taylor expansion around the average of $G(\alpha)$, average correlation can be approximated as a function decreasing linearly with the variance of the distribution of the α's, with the intercept and the slope increasing in the average α. Formally

$$\overline{\rho}(Z) \simeq \Upsilon(\bar{\alpha}) - K(\bar{\alpha})\text{var}(\alpha). \tag{10}$$

with $\Upsilon(\bar{\alpha}) > 0$, $K(\bar{\alpha}) > 0$, $\Upsilon(\bar{\alpha})_{\bar{\alpha}} > 0$ and $K(\bar{\alpha})_{\bar{\alpha}} > 0$, where $\Upsilon(\bar{\alpha})$ and $K(\bar{\alpha})$ are functions of average α_{ij}, average ξ_{ij} and ι (see appendix A3 for a formal definition).

It is possible to show that an increase in the variance of the distribution of α_{ij} increases the average pairwise correlation across sectors, while the effect of an increase in the average of $G(\alpha)$ has an overall negative effect on average correlation, determined by a direct positive effect and an indirect negative effect. The intuition behind such effects is the following: the larger the variance of the distribution of the α's, the more different the weights across sectors and the smaller the average correlation among the innovation processes across sectors. An increase in the average has a positive direct effect since the common factor becomes larger, and a negative effect since, as the average α increases, the weight of the variance term in (10) also increases.[18] All in all, the effect of an increase in both the first two moments of the distribution of the α's implies a lower probability that innovation occurs contemporaneously in different sectors in a small time interval. The increase of heterogeneity in α and therefore on diversification has an effect on the equilibrium of this economy. Before analyzing it in section 5, I need to determine the characteristics of the equilibrium. This task is accomplished in section 4.

3.4.2 The market for patents

Let v_{ij} be the value of the patent firm i obtains when innovating in sector j.[19] At each point in time, any firm (i) can perform research activity in sector j and attain a value v_{ij} with probability ι_{ij} by performing a certain idiosyncratic research effort (ξ_{ij}). To exert ξ_{ij} the entrepreneur has to hire ϕ_{ij} workers, while she has to hire just one worker to produce one unit of the improved quality. Heterogeneity across firms and sectors in the ability to enjoy general purpose technology (α_{ij}) and heterogeneity across sectors in the outside competition in the innovation race (ψ_j) implies that the value of the patent is heterogenous across firms and sectors, unlike Grossman and Helpman (1991).

[18] The overall effect is negative if the variance of the distribution of α's is large enough, that is if $\text{var}(\alpha) > 1/(3\iota\xi)$.

[19] Grossman and Helpman (1991) assume v as the stock market value of the firm. Since the focus of this paper is on diversification as risk-sharing device, it is more careful to talk about market value of the patent and market for a patent. If there were a stock market, if it were complete (non arbitrage condition), and access were unrestrained to any operator, workers would be able to smooth unemployment risk away via the stock market, as well as firms would be able to smooth the risk of being leapfrogged in the technological race. All is needed here is a resale value for the firm (a safe outside option), an expected profit and a capital gain, with the patent value depending on the latter two. Since the market for patents is highly competitive it has a sense to impose an arbitrage condition. Alternatively one can think of a complete stock market to which workers do not have access. Since profits are not distributed, workers do not have access to the stock market, not even indirectly through firms' ownership. Hence, firms are able to smooth away all risk, workers are not.

The dynamics of v_{ij} is characterized through the usual arbitrage equation, which compares revenues of the alternative investment strategies available to the entrepreneur, modified to take heterogeneity in v_{ij} into account. The expected gain of the leader at each period dt is equal to the expected profit from being a leader (Π) plus the capital gain of its investment ($\dot{v}_{ij}$) which is earned if no one else has innovated (which happens with probability $1-(\iota_j+\psi_j)dt$), minus the loss of the patent value if someone else in the city or outside innovates in sector j in dt (which happens with probability $\iota_j+\psi_j$), where $\iota_j=\int_0^1 \iota_{ij}di$ is the aggregate research effort in sector j in the city.[20] Therefore the expected gain of the leader is:

$$\Pi dt+\dot{v}_{ij}dt[1-(\iota_j+\psi_j)dt]-v_{ij}(\iota_j+\psi_j)dt \tag{11}$$

neglecting 2nd order effects, it becomes

$$[\Pi+\dot{v_{ij}}-(\iota_j+\psi_j)v_{ij}]\,dt \tag{12}$$

which at each dt has to be equal to the return on an outside safe investment

$$\Pi+\dot{v}_{ij}-(\iota_j+\psi_j)v_{ij}=rv_{ij} \tag{13}$$

$$\frac{\dot{v}_{ij}}{v_{ij}}=\iota_j+r+\psi_j-\frac{\Pi}{v_{ij}} \tag{14}$$

4 Equilibrium

In this economy the equilibrium is a set of values for the vector (w,ϕ_{ij},v_{ij},x,p) for given β, and a distribution for the random variable β, such that i) each R&D firm optimally chooses research employment to maximize the value of the patent, ii) each manufacturing firm maximizes profits (section 3.3), and iii) all markets (the one for final goods, the one for patents and the one for labor) clear. Sections 4.1 to 4.4 analyze in turn with such issues, while section 4.5 gives the intuition of the existence and uniqueness of the equilibrium, whose formal proof is confined in appendix A1.

4.1 Optimal R&D effort

The entrepreneur exerts the research effort in order to be able to enjoy the economic value v_{ij} of the patent she obtains. The optimal R&D effort schedule is recovered by choosing employment in research optimally to maximise $v_{ij}\iota_{ij}(\phi_{ij})dt-w\phi_{ij}dt$. Hence, for each firm and sector

$$\frac{\partial\iota_{ij}(\phi_{ij})}{\partial\phi_{ij}}=w/v_{ij},\quad\forall i,j \tag{15}$$

implicitly defines an optimal value of ϕ_{ij} and ι_{ij} for each value of v_{ij} given w, for each firm in each sector.

[20]Notice that probability of continuation is lower than in Grossman and Helpman (1991), and probability of being leapfrogged is higher when the outside world can innovate as well and the latter event is independent of the innovation in the city. Notice also that if the discovery rate of the outside competitor increases —i.e. its R&D technology becomes more productive, in equilibrium the idiosyncratic research effort of the entrepreneur in the city is lower as well as the value of the patent s/he detains.

As long as each firm neglects the spillovers coming from other firms research, (15) becomes

$$\frac{\partial \xi(\phi_{ij})}{\partial \phi_{ij}} = w/v_{ij}, \quad \forall i, j \tag{16}$$

which implicitly defines, for each firm in each sector, the optimal level of research employment ϕ_{ij} depending on the value of the patent v_{ij}; the exact values of both are pinned down by the equilibrium in the market for patents.

4.2 Final goods markets clearing

The optimal quantity produced by each leader is given by (5). The demand she faces is given by the demand expressed by all the consumers who are employed in research (inside and outside the city) plus the demand expressed by all those employed in manufacturing (inside and outside the city). That is, in each sector j

$$\begin{aligned} X^s_{\tilde{m}} = & \int_0^1 \int_0^1 \phi_{ij} \frac{w}{\lambda w_0} di dj + \int_0^1 \int_0^1 \eta \frac{w_0}{\lambda w_0} di dj \\ & + \int_0^\beta X^d_{\tilde{m}} \frac{w}{\lambda w_0} dj + \int_\beta^1 X^d_{\tilde{m}} \frac{w_0}{\lambda w_0} dj \\ = & \frac{w}{\lambda w_0} \phi + \eta \frac{w_0}{\lambda w_0} + \beta X^d_{\tilde{m}} \frac{w}{\lambda w_0} + (1-\beta) X^d_{\tilde{m}} \frac{w_0}{\lambda w_0}, \end{aligned} \tag{17}$$

where $\phi = \int_0^1 \int_0^1 \phi_{ij} di dj$. Neglecting the index for the best quality,

$$X = \frac{w\phi + \eta w_0}{(\lambda - 1 + \beta) \ w_0 - \beta \ w} \quad \text{for all } \ j \in [0, 1], \tag{18}$$

where I have assumed that R&D employment outside the city is η —that is, in the outside world η researchers are hired to exert a R&D effort $\psi_j = \psi_j(\eta)$, and I have imposed $X^s = X^d = X$.[21] As a consequence, using (6) one gets

$$\Pi = \frac{(\lambda w_0 - w)(w\phi + \eta w_0)}{(\lambda - 1 + \beta) \ w_0 - \beta \ w}, \quad \text{for all } \ j \in [0, 1]. \tag{19}$$

4.3 Patents market clearing

Equilibrium values for ϕ_{ij}, v_{ij} and then ι_{ij} are determined by the interaction between optimal effort in R&D (eq. (15)) and the equation describing the dynamics of the market value for the patent of newly invented quality (eq. (14)).

[21] Notice that production is positive since the denominator $(\lambda - 1 + \beta)w_0 - \beta w$ is always positive for $w < \hat{w}$, and $\hat{w} = w_0(\lambda - 1 + \beta)/\beta > \lambda w_0$.

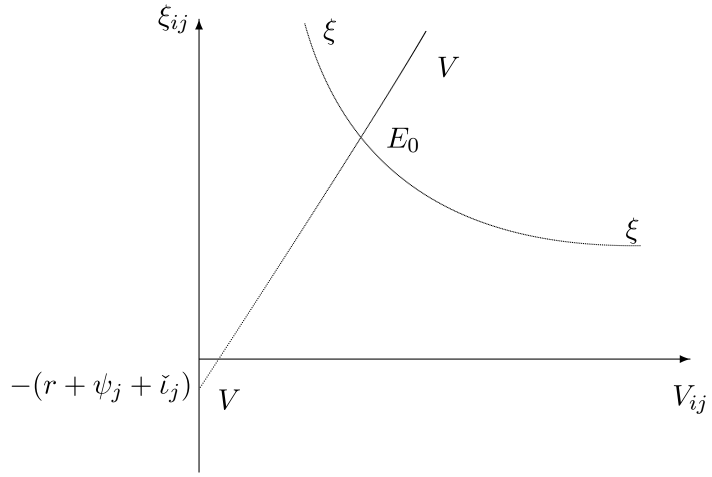

Figure 1: Optimal R&D effort and patent value

The equilibrium values of effort in R&D and patent value of the innovation are determined by the intersections between the two loci VV (obtained from (14) with $\dot{v}_{ij}/v_{ij}=0$ and $V_{ij}=1/v_{ij}$) and $\iota\iota$ (from (15)).[22] Formally,

$$\begin{cases} \dfrac{\partial \iota_{ij}(\phi_{ij})}{\partial \phi_{ij}} & = wV \\ \iota_j(\phi_{ij}) & = \Pi_j V - (r+\psi_j) \end{cases} \tag{20}$$

Since R&D spillover is neglected by the firm when choosing optimal spillovers and each entrepreneur investing in R&D is non atomistic,[23] (20) becomes

$$\begin{cases} \dfrac{\partial \xi(\phi_{ij})}{\partial \phi_{ij}} & = wV_{ij} \\ \xi(\phi_{ij}) & = \Pi V_{ij} - (r+\psi_j+\breve{\iota}_j) \end{cases} \tag{21}$$

where $\breve{\iota}_j = \alpha_{ij}\iota + \int_{p\neq i}[\alpha_{pj}\iota + \xi(\phi_{pj})]dp$ is taken as a constant by the single entrepreneur. Equilibrium is depicted as point E_0 in figure 1.

A condition implicitly defining ϕ^*_{ij} and V^*_{ij}, useful for comparative statics, can be obtained substituting the first equation into the second one, and inverting $\xi(\ )$. ϕ^*_{ij} and V^*_{ij} are therefore implicitly defined by

$$\phi^*_{ij} = \xi^{-1}\left[\frac{(\lambda\, w_0 - w)\,\phi_{ij}\,\xi_\phi}{(\lambda-1+\beta)\,w_0 - \beta\, w} + \frac{(\lambda\, w_0 - w)\,\eta V_{ij} w_0}{(\lambda-1+\beta)\,w_0 - \beta\, w} - (r+\psi_j+\breve{\iota}_j)\right] \tag{22}$$

[22] Using (15) one obtains $\partial\iota(\phi^*_{ij})/\partial V_{ij} = \iota_{\phi_{ij}} w/\iota_{\phi\phi} < 0$, that is $\iota\iota$ is downward sloping in the (V_{ij}, ι_{ij}) space. VV (the $\dot{v}_{ij}=0$ locus) is an upward sloping line in the same space (from (14)).

[23] This assumption means that i) the entrepreneur assumes as given the stock of general purpose knowledge (ι), while ii) she takes for given the contribution of all other agents aggregate sector j R&D effort $\int_{p\neq i}\xi(\phi_{pj})dp$ and iii) she consider its contribution $\xi(\phi_{ij})$ to it non negligible. This assumption allows the heterogeneity in R&D technologies to have full effect on equilibrium values of ϕ_{ij} and V_{ij}. Lamorgese (2007) provides the full treatment of alternative cases.

where $\xi_{\phi_{ij}} = \dfrac{\partial \xi(\phi_{ij})}{\partial \phi_{ij}}$.

4.4 Labor market clearing

Labor supply in the city is fixed at $\bar{L}$.[24] Since labor is indifferently used in both research and manufacturing, total labor demand in the city is the sum of demand for labor expressed by all the firms active in all sectors both in manufacturing and research. Employment in research is given by $\phi^* = \int_0^1 \int_0^1 \phi^*_{ij} didj$. Employment in manufacturing is equal to the sum of equilibrium quantities produced in each of the β sectors manufacturing a final good in the location. Therefore

$$\phi^* + \int_0^\beta X_{\tilde{m}}(j)dj = \phi^*(w) + \beta X(w) = \bar{L}$$

and substituting ϕ^* in (18)

$$\phi^* + \beta \frac{\phi^* w + \eta w_0}{(\lambda - 1 + \beta)w_0 - \beta w} = \bar{L}. \tag{23}$$

4.5 Existence and uniqueness of the equilibrium

The existence of an equilibrium in this economy can be verified by making sure that the labor market clears, i.e. that the two schedules $\beta X(w)$ and $\bar{L} - \phi(w)$ cross at least once in the (w, L) plan, within the set of admissible wage levels $[w_0, \lambda w_0]$. The first part of appendix A1 shows that the existence of the equilibrium is always guaranteed in this setting by showing that $\beta X(w)$ always exceeds $\bar{L} - \phi(w)$ at the minimum wage and is exceeded at the maximum wage.

Uniqueness also requires conditions on the relative slope and concavity of the two schedules. Whereas is it always possible to show that $\bar{L} - \phi(w)$ slopes positively and to give reasonable conditions under which the slope of $X(w)$ is determined, in the general case the conditions for which the concavity of both schedules is determined bear little economic meaning.[25]

For the remainder of the paper, it is assumed that the idiosyncratic component of R&D technology is equal to $\xi(\phi) = \log(\phi)$, which assures uniqueness of the equilibrium within the admissible wage range, as depicted in figure 2. The second part of appendix A1 gives a formal proof of uniqueness of the equilibrium.

5 Discovery of new qualities, dynamics of the market share and diversification

So far the paper has established a formal relation between the moments of the distribution $G(\alpha)$ and average correlation among innovation processes (section 3.4.1) and been showed that this economy admits one equilibrium for given β (section 4). In this section I reap the main result of the paper, that is I analyze the effect of an increase in diversification in R&D technology

[24] Labor supply is indeed $\int_0^1 \bar{L} \ \ dh$ for $w \geq \underline{\underline{w}}$, and 0 otherwise.

[25] Still in the general case, uniqueness and stability of the equilibrium are assured at least in a subregion of the parametric space (Lamorgese, 2001).

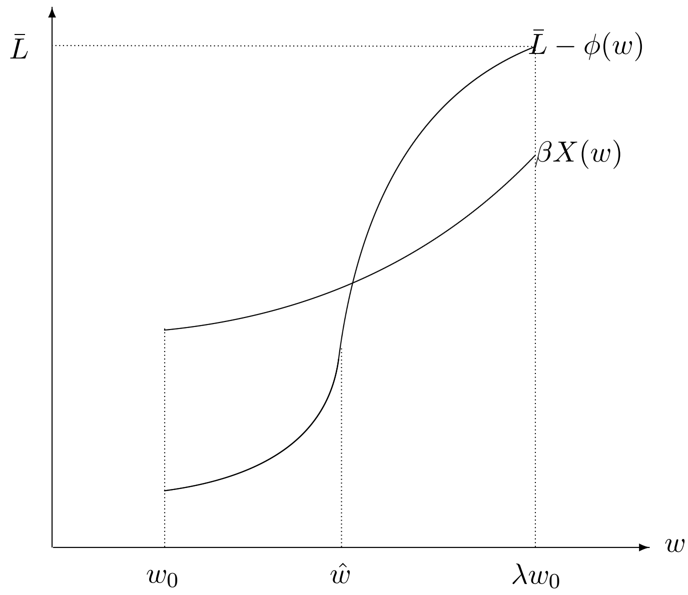

Figure 2: Equilibrium in the labor market

on the equilibrium local employment and output; in so doing, I am able to assess the effect of increase in diversification in R&D technology on the volatility of the local labor market and the city aggregate business cycle.

Before achieving this result, I need to establish an intermediate result, that is I need to assess the effect on the equilibrium of an exogenous change —triggered by the relocation of production between the city and the outside world— in the share of production in the city β, which so far as been taken as given.[26] Although this exercise gives the reader the flavor of the mechanisms triggered by a change in the share β of production in the city, a caveat needs to be taken in account: the share β of production in the city in this setting is not exogenous, but it is endogenously determined by the equilibrium values of ϕ_{ij} given $\bar{L}$, λ, η and ψ_j and the randomness of innovation, which is the engine of the whole process of industry relocation and depends on R&D employment.[27] Should the focus be long-run growth, the model should therefore be solved dynamically taking β as endogenous;[28] since here I am only interested in the effect of diversification in R&D on short-run fluctuations of output and employment, I can safely consider β as exogenously given.

Starting from an equilibrium of this economy, with $w = w_1$ and $\beta = \beta_1$, I suppose that

[26] I only consider the case in which innovation drives up the share of production in the city —the case of a drop of β being symmetrical.

[27] Random innovation feeds the economy with random shocks —i.e. the discovery of a new quality— at random intervals: if discovery occurs in a sector which was not producing in the city, an entrepreneur sets up a manufacturing firm, and this induces endogenous increase in β; if it occurs in a sector already producing in the city, the new manufacturer just replaces the old one and β is unchanged; if, finally, the innovation is achieved by firms in the outside world in a sector whose production takes place in the city β decreases.

[28] If the endogeneity of the local share of production is taken into account, β turns out to evolve as a Markov process with a continuous state space. Preliminary results of a simpler set-up with up to four sectors (states) and a unit mass of firms in each sector suggest that the distribution of β is ergodic and convergence to the ergodic distribution is rather fast.

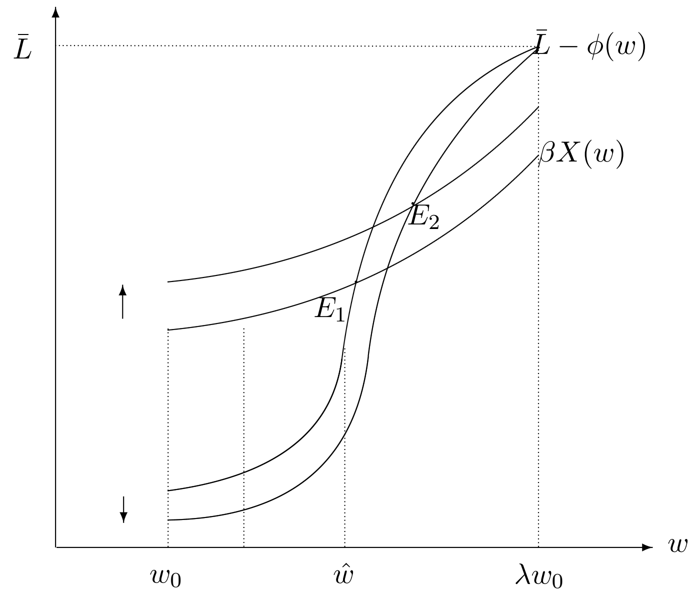

Figure 3: Change in the local share of production and equilibrium in the labor market

an entrepreneur located in the city discovers a new quality in an industry which is currently producing outside the city, thus making β increase from β_1 to β_2.

On the spot, for given $w = w_1$, profits increase and so also does the incentive to perform R&D, thus causing the demand for researchers to increase ($\partial\phi^*/\partial\beta > 0$, by lemma 1, in appendix A2). Aggregate demand for final goods increases as a consequence, since there is a larger demand for goods from an increased number of R&D employees, and by a larger number of firms in production. Labor demand in turn increases through three channels, i.e. i) increased demand for researchers (i.e. in increase in ϕ in $\phi + \beta X$); ii) increased demand for manufacturers, since more firms are producing in the city (i.e. an increase in β); and iii) increased demand for manufacturers, since more researchers and more producers are demanding more goods which need to be produced (i.e. an increase in X). Such changes affect both the LHS and the RHS of the equilibrium condition in the labor market, namely $\beta X(w)$ is shifted up, while $L - \phi^*(w)$ is shifted down (see figure 3).

At wage w_1 labor demand exceeds labor supply, thus driving wages upward and restoring a new equilibrium at an higher wage through a reduction of employment in research (by equation (37)), and an increase of employment in production (by equation (35)).

I am now ready to analyze the effect of an increase in diversification in R&D technology on the equilibrium local employment and output.

In section 3.4.1 a formal relationship has been derived between the moments of the distribution of the α's, which proxy the degree of diversification in R&D in the city, and the average correlation among innovation processes. According to it, the more (less) dispersed $G(\alpha)$, the higher (lower) the diversification in R&D technology, and the lower (higher) average correlation among innovation processes in the city.

Turning to the effects of diversification in R&D on the equilibrium, a lower (higher) average correlation in innovation processes induces a smaller (larger) number of innovations within the unit of time, a smaller (larger) share of production located in the city, a smaller (larger) pressure on wages, and a smaller (larger) crowding out of R&D employment by employment in production; less (more) crowding out induces in turn a larger (smaller) probability of innovation of local R&D activity and higher (lower) future competitiveness of city products. Finally, more (less) diversification in R&D technology along with a smaller (larger) number of contemporaneous innovations induces less (more) volatility in employment and in the production share in the city.[29]

6 Extensions

In this section two further issues are tackled within the framework of this model. Section 6.1 shows how to integrate learning by doing and knowledge accumulation in the model; in so doing the trade-off between diversification and labor market fluctuations is less severe and specialization arises in the model. Section 6.2 extends the main results of the model to a case where there exist two labor factors (skilled and unskilled labor) featuring different degrees of intercity mobility.

6.1 Learning by doing and specialization

So far the model predicts that both workers and entrepreneurs prefer more diversification. This could be seen as contradicting empirical evidence which suggests a pattern of concentration and specialization depending on the stage of the life cycle: specialization would be a characteristic of the early stages of the life cycle of a city, whereas diversification would prevail in mature cities (Glaeser, Kallal, Scheinkman and Shleifer, 1992).

Specialization can be accounted for in this model considering that innovation becomes tougher and tougher to achieve the further the technological frontier is pushed (Segerstrom, 1998, for an analogous treatment of the technological frontier). This is obtained posing

$$\iota = \iota(h, \phi), \quad \iota_1 > 0, \iota_2 > 0, \iota_{11} < 0, \iota_{22} < 0 \tag{24}$$

where h is the state of art and ϕ is the number of workers. Research intensity is increasing in the state of art and the number of researchers employed, but productivity is decreasing in both arguments. State of the art is specific to the sector in which is accumulated. State of the art accumulates while performing research, but the more advanced the state of the art, the slower the accumulation, that is

$$\dot{h} = \iota(h, \phi) - \gamma h.$$

Each firm decides the employment of researchers —which still are undistinguished from manufacturing workers— solving the following dynamic problem:

[29] It is also possible to show that less (more) technological diversification induces smaller (larger) growth rates of output (as in Aghion and Howitt, 1992): when the production share increases, production crowds out research; when production shares decreases because of leapfrogging, and R&D's reward is high from an individual point of view, firms anticipate that the large research effort induced by larger individual investment and a large cross sector spillover shortens the period during which monopoly profits are reaped, and invest less. This way one observes low research in both cases, and the city is trapped in a low growth regime.

$$\max_{\phi_t} \int_0^{+\infty} \big[v_t \iota(h_t, \phi_t) - w\phi_t\big] dt \tag{25}$$

$$\text{s.t. } \dot{h} = \iota(h, \phi) - \gamma h \tag{26}$$

$$h_0 = \phi_0 = 0. \tag{27}$$

The Hamiltonian of the problem and the set of first order conditions are (hereafter, I will neglect time indexes)

$$H = v\iota - w\phi + \mu(\iota - \gamma h) \tag{28}$$

$$H_\phi = 0, \quad v\iota_\phi - w + \mu\iota_\phi = 0 \Rightarrow \iota_\phi = \frac{w}{v+\mu} \tag{29}$$

$$H_h = -\dot{\mu}, \quad -\dot{\mu} = v\iota_h - \mu\gamma \Rightarrow \dot{\mu} = \mu\gamma - v\iota_h \tag{30}$$

to which (26) has to be added.[30] To guarantee asymptotic stationarity, one must choose the backward solution to (26) and the forward solution to (30). The solution is given by

$$h(t) = k_0 e^{-\gamma t} + \int_{-\infty}^{t} e^{\gamma(s-t)} \iota(s) ds \tag{31}$$

$$\mu(t) = k_1 e^{\gamma t} + \int_t^{+\infty} e^{\gamma(t-s)} \iota_h(s) ds \tag{32}$$

together with (29).[31]

These equations teach two lessons of the model. First, depending on the past history of research effort, the level of the state of the art increases (equation (31)). This has a negative effect on ι_h ($\iota_{hh} < 0$) and through (32) on μ. ι_ϕ increases as a consequence, and by the concavity on the R&D technology in both the arguments delivers smaller demand for researchers in the equilibrium. As long as the state of the art becomes more complex (the technology becomes more mature) firms want to employ less researchers. The gain from invention decreases to the point that it is less convenient to perform research in that sector. Second, when technology is still young, the state of the art is low, the productivity of h in R&D is high, μ is high, ι_ϕ is low and more researchers are demanded by each firm. As long as the state of the art is not very well developed it is very convenient to perform research and firms bid up to hire researchers, which is the only input of R&D they can change discretely.

These considerations have a consequence on the dynamics of employment and wages in the local market and feed back on the incentive to perform research in the city. As h is low, each firm wants to employ more researchers and this boosts aggregate employment in research, reducing the size of the idle labor force and squeezing the room for another sector to invent and produce in the city. Firms of another sector anticipate that labor demand is too high in the city for them to take advantage from settling in. On the other hand, there is no spillover to catch, therefore from their viewpoint there is no advantage in choosing that site to produce. The city ends up being specialized in the young technology.

[30] Second order conditions can be shown to be verified using (24) and the Mangasarian's (1966) conditions.

[31] Notice that (29) describe the demand for researchers on the local labor market, and it is well behaved. It turns out to be decreasing in wages and increasing in the market value of the patent of the hiring firm: firms hire less researchers if their wage increases, but they hire more of them when the perception of the market value of the patent detained is larger.

As long as the technology becomes mature, h increases, the incentives to hire researcher slow down. Employment in the city decreases and this eventually creates enough room for another sector to settle in and perform research. Cities featuring mature technologies end up being more diversified than cities featuring upstart new technologies.

6.2 Skilled vs. unskilled workers

The trade off between specialization and fluctuations is also mitigated by the consideration of two different kinds of labor, skilled workers and unskilled workers. Skilled workers are supposed to be freely mobile across cities, while unskilled workers are city specific. It is also supposed that both kinds of workers are used both in production and R&D and that they are imperfect substitutes.[32]

In this different setting specialization happens at the cost of growing wages both for mobile and immobile workers. Suppose that a new quality is discovered in the city: a new leader takes the world demand for that good at the expenses of the former leader which is located abroad. The latter releases both mobile and immobile labor. The innovator attracts immobile workers by bidding in the local market, mobile workers by bidding in the world market. Bidding in the local labor market pushes immobile workers wages upward to a larger extent than in the international markets where workers are released from the former leader. Since the new leader can partially substitute mobile and immobile workers, wages of both are in the end pushed upward by the same extent, and research becomes more expensive. The consequences are the same as in the main model, but i) wage revisions are dampened by the presence of a mobile resource; ii) by a general equilibrium consideration wage is pushed upward in both locations (abroad the mobile factor has to be paid a higher wage, therefore it is substituted away with immobile labor, whose price is pushed upward); iii) volatility in the labor markets for both factors in both cities is dampened by the possibility to substitute the relatively more expensive factor with the cheaper one.

The last result depends crucially on the elasticity of substitution among the factors. If mobile and immobile workers are perfect substitutes, it is as if only one kind of labor is used, and specialization plays no role, since the supply of mobile workers is not scarce. If mobile and immobile labor are not substitutes at all (think of a Leontief's production function), volatility increases only in the market for the immobile factor. In this case only the immobile factor enjoys the city as a diversification device, the mobile factor being indifferent between settling in a specialized or diversified city.

7 Concluding remarks

This paper shows a mechanism through which the absence of diversification in R&D technology induces correlated product life cycles in different sectors. Such a comovement has two implications. On the one hand, city life cycle is tightly linked with these comoving product life cycles, whose fluctuations are large and depend on competition of the markets for final goods. On the other hand, during booms the general equilibrium effect of the increased demand for labor drives

[32] Different modeling choices imply sharply different results. If mobile workers are only used in R&D, and immobile workers are only used in production, specialization drives up immobile workers wage, but at the same time does not discourage research. Specialization ceases to be harmful for R&D and future competitiveness of the city.

wages upward, discouraging R&D and undermining future competitiveness of the city.

Diversification in R&D technology across sectors —which unchains the life cycle of the city from the product life cycle of the activities performed within the city, since aggregate output does not comove with sectoral output— reduces volatility of employment and wages. General equilibrium effects of higher demand on the local labor market are dampened, the effort locally exerted in R&D is higher, and city output grows through less volatile cycles.

Such a trade-off between diversification and business cycle fluctuations is influenced by two features of the model, namely pecuniary externality and learning by doing. The pecuniary externality which arises in the model once expenditure is made endogenous, is shown to exacerbate the above mentioned trade-off: the adjustment toward equilibrium after a new innovation is accompanied by higher wage pressure and higher employment volatility the stronger the pecuniary externalities. Conversely, learning by doing and the possibility to accumulate knowledge over time make the trade-off less tight. Learning by doing compensates the negative effect of competition in the local labor market on the incentives to perform R&D.

Two further issues are left out of the analysis: the effect of allowing mobility of the labor force (migration) and the consideration of a complete market for capital. Migration would allow a reduction in the negative effects of increased demand in the local labor market, because local labor supply would not be bounded from above, except in the very short period. This feature would then work in the direction of weakening the trade-off between the absence of diversification and incentive to perform R&D, output growth and employment. This is a standard result indeed: human capital flows play the role of an income smoothing device, like a complete market for asset and cross- ownership would do. This latter would introduce a more reliable and easier device to insure against boosts in the city life cycle. Inhabitants of a city would be able to share risk by just detaining shares in activities performed outside the city. Given the structure of the competition in the market for goods (there is only one winner of the technological race in each sector), those shares would represent a perfect contingent claim. Absence of diversification would not be harmful anymore, in that it would still reduce competitiveness inside the city, but without the negative consequences on the level of local expenditure which are peculiar to the model developed in the paper.

Appendix

A1 Proof of existence and uniqueness of the equilibrium

Existence

One way to verify that the equilibrium exists is to compare $\beta X(w)$ and $\bar{L} - \phi(w)$ at $w = w_0$ and $w = \lambda w_0$, evaluating (17) at the extremes of the wage range. One thus obtains:

$$\beta X(w_0) = \beta \frac{\phi(w_0) + \eta}{\lambda - 1} \geq \bar{L} - \phi(w_0) \tag{33}$$

$$\beta X(\lambda w_0) = \beta \frac{\eta}{(\lambda - 1)(1 - \beta)} \leq \bar{L}. \tag{34}$$

To obtain the latter recall that at $w = \lambda w_0$ profits as well as employment in R&D are nil.[33]

The first condition amounts to require that at the minimum wage labor demand exceeds labor supply. By the definition of w_0 in footnote 11, when no production occurs in the city (i.e.

[33] Also notice that $X(\lambda w_0)$ is limited from above at $(\beta\eta + \bar{L}\beta\lambda)/(\lambda - 1 + \beta)$ since employment in production in the city is at most $\bar{L}$.

$\beta = 0$) $\bar{L} = \phi(w_0)$, implying that $\beta X(w_0) \geq \bar{L} - \phi(w_0)$ for any $\beta \in [0, 1]$.

The second condition requires that at the maximum wage there are in the city enough workers to satisfy world demand for the bundle of production goods produced in the city. Should the latter not be the case, since the price of the top quality cannot exceed λw_0 without diverting demand to the second highest quality, production of such goods in the city would therefore satisfy world demand up to $\bar{L}$, with the remaining world demand $\beta\eta/(\lambda - 1)(1 - \beta) - \bar{L}$ being satisfied by firms outside the city producing the second-best-quality at the limit price w_0.

Hence, $\beta X(w)$ exceeds $\bar{L} - \phi(w)$ at $w = w_0$, while the former is at least as large as the latter at $w = \lambda w_0$, implying that the two schedule cross at least once in $[w_0, \lambda w_0]$. This establishes the existence of an odd number of equilibria in the admissible wage range.

Uniqueness

Before giving the formal proof of uniqueness in the case of a logarithmic R&D technology, it is instructive to examine the reason why in the general case it is hard to evaluate the slope of demand for labor in production with respect to wages.

An increase (decrease) of wages diminishes (increases) demand for researchers, and —owing to the pecuniary externality— commands a higher demand for goods, and therefore for manufacturing workers who produce them. In turn each manufacturer is paid a higher wage and demands more goods. All in all, potentially, the increased demand for manufacturing workers may outweigh the reduction in the demand for researchers. If this is the case, the increase in wages initially meant to reduce labor demand ends up increasing it. On the opposite, wages decrease if upward wage pressure reduces demand for researchers more than it increases demand for manufacturers.

The intuition of such a mechanism is easily got by observing that the derivative of labor demand in production with respect to wages is due to the combination of three effects:

$$\frac{\partial X}{\partial w} = \frac{1}{\big[(\lambda - 1 + \beta)\, w_0 - \beta w\big]} \left[\phi^* + w\frac{\partial \phi^*}{\partial w} + \beta X\right]. \tag{35}$$

The first term in brackets represents a kind of wealth effect of the increase of wages on the demand of production goods by R&D workers: keeping R&D employment constant, expenditure by R&D workers increases along with their payroll, and the increased demand for goods commands a higher demand for production workers. The second term represents a sort of substitution effect of the wage increase on the demand of goods by R&D workers: according to equation (37), a wage increase induces a shrink in the R&D employment, thus for constant wage the demand for goods by R&D workers decreases, thus commanding a lower demand for production workers. The third term represents a multiplier effect: higher wages increase expenditure on production workers, thus commanding an higher demand for goods which has to be met by an increase of employment in production.

Intuitively, for the demand for production workers to decrease due to a wage increase, the demand for R&D workers has to decrease much more then proportionally than the wage increase. Should this be the case, the substitution effect would more than compensate the wealth effect and the multiplier effect, and excess demand of labor would be re-equilibrated via wage changes.

Moving to a logarithmic R&D technology, the obvious advantage of such functional form is that the wealth effect and the substitution effect in (35) cancel out, thus leaving the slope of labor demand in manufacturing be determined by the only multiplier effect.

Formally, (16) must hold at the equilibrium, therefore $\partial\phi^*/\partial w = -\int_0^1\int_0^1 1/(w^2 V_{ij})\,di dj$ and $\phi^* = \int_0^1\int_0^1 1/(wV_{ij})\,di dj$; the first and the second term in (35) cancel out, implying that the sign of the partial derivative of the demand for labor in production depends on the sole sign of the multiplier effect, which is always positive.

By the same token, demand for labor in production is concave in wages since

$$\begin{aligned}\frac{\partial^2 X(w)}{\partial w^2} &= \beta\Big\{\frac{\dfrac{\partial \phi^*}{\partial w}w + \phi^*}{[(\lambda-1+\beta)w_0-\beta w]^2} + 2\beta\frac{\phi^* w + \eta w_0}{[(\lambda-1+\beta)w_0-\beta w]^3}\Big\}\\ &= 2\beta^2\frac{\phi^* w+\eta w_0}{[(\lambda-1+\beta)w_0-\beta w]^3} > 0. \end{aligned} \tag{36}$$

Hence demand for workers in production is a monotonically increasing function of the wage level.

Turning to $\phi(w)$, $\xi_\phi(\phi) = 1/\phi$ can be replaced into (22), so that the equilibrium level of employment in research becomes

$$\phi^* = \int_0^1\int_0^1 \exp\Big\{B(w)(1+\eta w_0 V) - (r+\psi_j+\breve{\imath}_j)\Big\}didj,$$

$$\text{where} \quad B(w) = \frac{\lambda w_0 - w}{[(\lambda-1+\beta)w_0-\beta w]}.$$

It is easy to show that the employment in research decreases as wage increases, and that the schedule $\bar{L} - \phi^*(w)$ is increasing in wage. Formally,

$$\begin{aligned}\frac{\partial \phi^*(w)}{\partial w} &= \frac{\partial}{\partial(w)}\int_0^1\int_0^1 (1+\eta w_0 V_{ij})B(w)\exp\Big\{B(w)(1+\eta w_0 V_{ij}) - (r+\psi_j+\breve{\imath}_j)\Big\}didj\\ &= -\int_0^1\int_0^1 C\frac{\phi^*_{ij}}{[(\lambda-1+\beta)w_0-\beta w]^2}didj < 0\end{aligned} \tag{37}$$

where $C = (\lambda-1)(1-\beta)(1+\eta w_0 V_{ij})w_0 > 0$.[34]

The sign of the second derivative of employment in research with respect to wage depends on the minimum wage w_0, namely

$$\frac{\partial^2\phi^*(w)}{\partial w^2} = -\int_0^1\int_0^1 C\frac{-C\phi^*_{ij} + \phi^*_{ij}2\beta[(\lambda-1+\beta)w_0-\beta w]}{[(\lambda-1+\beta)w_0-\beta w]^4}didj$$

replacing (37) and collecting ϕ^*

$$\frac{\partial^2\phi^*(w)}{\partial w^2} = -\int_0^1\int_0^1 \phi^*_{ij}Cdidj\frac{2\beta[(\lambda-1+\beta)w_0-\beta w] - (\lambda-1)(1-\beta)(1+\eta w_0 V)w_0}{[(\lambda-1+\beta)w_0-\beta w]^4}$$

where $V = \int_0^1\int_0^1 V_{ij}didj$, from which is apparent that

$$\text{sign}\{\frac{\partial^2\phi^*(w)}{\partial w^2}\} = -\,\text{sign}\Big\{2\beta[(\lambda-1+\beta)w_0-\beta w] - (\lambda-1)(1-\beta)(1+\eta w_0 V)w_0\Big\}$$

[34] The derivative of V_{ij} and $\breve{\imath}_j$ with respect to w do not need to be considered as an application of the envelope theorem.

Demand for researchers turns out to be concave (and the schedule $\bar{L}-\phi(w)$ convex) for $w < \hat{w}$ where

$$\hat{w} = \frac{2\beta(\lambda - 1 + \beta) - (\lambda - 1)(1-\beta)(1+\eta w_0 V)}{2\beta^2} w_0.$$

Obviously $\hat{w}$ does not need to lie within the admissible wage range, therefore three cases should be distinguished: i) if $w_0 < (2A\beta - 1)/(\eta V)$ than $\hat{w} > \lambda w_0$, therefore it is always $w < \hat{w}$ and $\bar{L} - \phi(w)$ is convex; ii) if $(2A\beta - 1) < w_0 < (2A\beta - \beta + 1)/[(\eta V)(1-\beta)]$ than $\hat{w} \in [w_0, \lambda w_0]$ and $\bar{L} - \phi(w)$ is S-shaped, namely convex for $w < \hat{w}$ and concave otherwise ; finally iii) if $w_0 > (2A\beta - \beta + 1)/[(\eta V)(1-\beta)]$, then $\hat{w} < w_0$, therefore $w > \hat{w}$ and $\bar{L} - \phi(w)$ is always concave.

In each of the three cases, however, $\beta X(w)$ and $\bar{L} - \phi(w)$ have one and only one cross-point, and the equilibrium is unique.

A2 Employment in research and production when the β increases

Lemma 1
When β increases, employment in R&D and demand in manufacturing increase.

Proof of the lemma 1
For given ϕ, by equation (19),

$$\frac{\partial \Pi(w,\beta)}{\partial \beta} = \frac{(\lambda w_0 - w)(\phi w + \eta w_0)(w - w_0)}{[(\lambda - 1 + \beta)w_0 - \beta w]^2} > 0$$

Recalling figure 1, The $\xi\xi$ locus stays put, while the VV locus turns counterclockwise around the intercept. The new equilibrium in the market for patents occurs at an higher employment in research and an higher value of the patent (V decreases, v increases).

Turning to employment in production, having just shown that $\partial\phi^*/\partial\beta > 0$,

$$\frac{\partial}{\partial \beta}\ \beta X(\beta, w_0) = \big[1 + \frac{w - w_0}{(\lambda - 1 + \beta)w_0 - \beta w}\big]X + \frac{w\dfrac{\partial \phi}{\partial \beta}}{(\lambda - 1 + \beta)w_0 - \beta w} > 0$$

□

A3 The relation between average correlation among sectors and the variance of α

Let $corr(Z_{ij} Z_{sn})$ in equation (9) be written as a function of $(\alpha_{ij}, \alpha_{sn})$, $\Gamma(\alpha_{ij}, \alpha_{sn})$ and let the average correlation in (10) be written as

$$\begin{aligned}
\overline{\rho}(Z) &= \int\int corr(Z_{ij} Z_{sn}) f(\alpha_{ij}, \alpha_{sn}) d\alpha_{ij} d\alpha_{sn} \\
&= \int\int \Gamma(\alpha_{ij}, \alpha_{sn}) f(\alpha_{ij}, \alpha_{sn}) d\alpha_{ij} d\alpha_{sn} \\
&= \int\int \Gamma(\alpha_{ij}, \alpha_{sn}) f(\alpha_{ij}) f(\alpha_{sn}) d\alpha_{ij} d\alpha_{sn}
\end{aligned}$$

since α_{ij} and α_{sn} are iid (which also implies that $cov(\alpha_{ij}, \alpha_{sn} = 0)$). Consider the second order Taylor approximation of $\Gamma(\alpha_{ij}, \alpha_{sn})$ in a neighborhood of $E(\alpha) = \bar{\alpha}$,

$$\Gamma(\alpha_{ij}, \alpha_{sn}) \simeq \Gamma(\bar{\alpha}, \bar{\alpha}) + \nabla\Gamma(\bar{\alpha}, \bar{\alpha})'[\alpha_{ij} - \bar{\alpha}, \alpha_{sn} - \bar{\alpha}]' + \frac{H}{2}\Gamma(\bar{\alpha}, \bar{\alpha})'[(\alpha_{ij} - \bar{\alpha})^2, (\alpha_{sn} - \bar{\alpha})^2]'$$

$$\begin{aligned}\overline{\rho}(Z) \simeq{}& \Upsilon(\bar{\alpha}) + D(\bar{\alpha})\left[\int (\alpha_{ij} - \bar{\alpha}) f(\alpha_{ij}) d\alpha_{ij} + \int (\alpha_{sn} - \bar{\alpha}) f(\alpha_{sn}) d\alpha_{sn}\right] \\ & - \frac{K(\bar{\alpha})}{2}\left[\int (\alpha_{ij} - \bar{\alpha})^2 f(\alpha_{ij}) d\alpha_{ij} + \int (\alpha_{sn} - \bar{\alpha})^2 f(\alpha_{sn}) d\alpha_{sn}\right]\end{aligned}$$

where $\bar{\xi} = \int\int \xi(\phi_{ij}) di dj$, $\Upsilon(\bar{\alpha}) = \dfrac{\bar{\alpha}^2\iota}{\bar{\alpha}^2\iota + \bar{\xi}} > 0$, $D(\bar{\alpha}) = \dfrac{\bar{\alpha}\iota\bar{\xi}}{(\bar{\alpha}^2\iota + \bar{\xi})^2} > 0$, $K(\bar{\alpha}) = \dfrac{3\bar{\alpha}^2\iota^2\bar{\xi}}{(\bar{\alpha}^2\iota + \bar{\xi})^3} > 0$.

Hence,

$$\overline{\rho}(Z) \simeq \Upsilon(\bar{\alpha}) - K(\bar{\alpha})\,\mathrm{var}(\alpha).$$

Also notice that $\dfrac{\partial\Upsilon(\bar{\alpha})}{\partial\bar{\alpha}} = \dfrac{2\bar{\alpha}\iota\bar{\xi}}{(\bar{\alpha}^2\iota + \bar{\xi})^2} > 0$, $\dfrac{\partial K(\bar{\alpha})}{\partial\bar{\alpha}} = \dfrac{6\bar{\alpha}\iota^2\bar{\xi}^2}{(\bar{\alpha}^2\iota + \bar{\xi})^2} > 0$.

Finally, notice that the third order Taylor approximation delivers a positive dependence between the average pairwise correlation $\bar{\rho}(Z)$ and the skewness of the distribution of the α's through the coefficient $G(\bar{\alpha}) = \dfrac{\bar{\alpha}\iota^2(4\bar{\alpha}^2\iota + \bar{\xi})\bar{\xi}}{(\bar{\alpha}^2\iota + \bar{\xi})^4} > 0$, while the fourth order approximation establishes a negative correlation with the kurtosis, through the coefficient $M(\bar{\alpha}) = \dfrac{5\bar{\alpha}\iota^3\bar{\xi}(3\bar{\xi} - 4\bar{\alpha}\iota)}{4(\bar{\alpha}^2\iota + \bar{\xi})^5} < 0$.

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