Innovation and Knowledge Spillover with Geographical and Technological Distance in an Agentbased Simulation Model

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Abstract

The paper introduces an agent-based simulation model to study the technological development and the economic performance of firms with potential knowledge spillover in a differentiated industry. The analysis is based on the interaction and behavior of firms, which might share knowledge but at the same time are competitors on the goods markets. The aim of the model is to get a better understanding of the interplay between technological and geographical location decisions and the evolution of specific knowledge in an industry. For this the advantages and disadvantages of two forms of distances are discussed: geographical and cognitive respectively technological distance. First simulation runs indicate that the model is able to describe the technological development and produces plausible industry characteristics. It is shown that geographical proximity enhances innovation, especially the number of product innovations.

Keywords: Innovation, Learning, Knowledge Spillover, Agent-based Simulation, Industry Dynamics
JEL Classification: D83, O31, O32, R10

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1 Introduction

Innovation and technological change seem to be crucial for understanding economic growth. This paper introduces an agent-based model in order to study the interplay between technological and geographical location decisions and the evolution of specific knowledge in an industry.

Geographical and technological proximity are seen as main factors fostering innovation[1], because both kinds of proximity have an impact on the learning capabilities of firms. Beside investments in Research and Development (R&D) learning allows firms to accumulate knowledge which is the precondition for generating successful innovations: either to raise productivity through process innovation or to attract new consumer groups with new products through product innovations. Knowledge is inherently different from the more traditional inputs of labor, capital, and land: knowledge is intrinsically uncertain, it is asymmetric allocated between economic agents, it is cumulative and can be transmitted voluntary or involuntary (at least over some geographical distance) without loosing any value (see Dosi, 1988b). In order to catch all relevant effects of innovation the model has to take into account this particular characteristics of knowledge.

The empirical literature suggests that geographical proximity leads to a faster diffusion of knowledge through spatially bounded knowledge spillover. A recent survey by Asheim and Gertler (2005) even claims: *"..one simply cannot understand innovation properly if one does not appreciate the central role of spatial proximity and concentration in this process."* Based on these observations a core-periphery pattern is used, so that firms can either choose a location in the core or in the periphery. The core may also be understood as a cluster or network, where all firms might profit from the knowledge of each other. The concentration of firms in the core leads to higher production cost resulting from shortage of scarce resources. On the other hand firms can choose a location in the periphery with lower production cost, but then they cannot increase their knowledge with external spillover. If a firm chooses isolation, it will however not loose their technological core competence via involuntary knowledge spillover.

The cognitive or technological distance seems to be significant for the learn-

[1]For a recent overview see Boschma (2005)

ing process, too. The amount of knowledge a firm is able to use economically is described by the absorptive capacity (see Cohen and Levinthal, 1989, 1990). The concept of absorptive capacity sets a lower bar for the firm's knowledge heterogeneity. But the learning effect is also reduced if a firm wants to absorb very similar knowledge. The heterogeneity of knowledge should be *"sufficiently small to allow for understanding but sufficiently large to yield non-redundant, novel knowledge"* (Nooteboom, 2000, p. 72). The results of the knowledge exchange process could be described as an inverse U-shaped relation depending on technological distance. The heterogeneity of knowledge can be expressed by the technological distance, measured by the path between two technologies in a technology space and the technological gap between the knowledge stock of two firms in these technologies. Both elements are relevant for the resulting learning effect through knowledge spillover.

In the past, industry simulation models which considered knowledge spillover with geographical and/or technological distance were often based on a cellular automata framework, e.g. Verspagen (1993); Keilbach (2000); Brenner (2001); Caniëls and Verspagen (2001) and Meagher and Rogers (2004) present simulation models with innovation in a spatial landscape. Other approaches like Cantner and Pyka (1998a,b) describe industry dynamic models with heterogeneous knowledge spillover. Here a product market was modelled while focussing either on the absorptive capacity of firms or the selection process with different technologies. Jonard and Yildizoglu (1998) and Zhang (2003) introduce extensions of the traditional Nelson and Winter (1982) model with a technological space and spatially bounded knowledge externalities. Gilbert et al. (2001) describe the interaction of agents with a specified knowledge base in an innovation network. This paper combines elements of these simulation studies while concentrating on the interaction on differentiated product markets and strategic location of firms in the sense of geographical and technological distance.

The methodology of agent-based simulation is particularly useful in connection with modelling innovation and knowledge spillover, because it enables to describe the intrinsic uncertainty, the cumulative structure and the dynamics involved in innovation processes (see Dosi, 1988a), the endogenously changing market structure (see Klepper, 1996) and the heterogeneity of knowledge, which is essential for learning (see Nooteboom, 2000).

The paper is organized as follows. In the next section 2 the model is introduced. The description of the model contains the role of knowledge, the circular technology space, the calculation of knowledge spillover, the market demand and cost structures, as well as the decision making of firms and finally the market clearing. Section 3 shows the setup for the simulation studies. First results of the simulation runs can be found in section 4. The paper closes with the main conclusions.

2 The Model

In order to deal with the effects of geographical and technological distance an industry-simulation model is introduced. The model is based on Dawid and Reimann (2003, 2004) with the extension of heterogeneous knowledge spillover. The production side of the industry is represented by an agent-based model allowing for heterogeneities of location, cost-structures, strategies concerning production and R&D among the industry firms. The demand side is highly stylized employing the concept of a representative consumer.

2.1 Knowledge and Innovations

The knowledge of firms is one of the most important elements of the model. Each firm holds a technological profile, which represents the capabilities for innovations. On the one hand the company may introduce a new method, which leads to lower production cost, or it presents a better version of an existing product. On the other hand the firm wants to launch a brand-new product in order to meet the needs of new consumer groups. The first part of the technology profile is captured by a knowledge stock for process innovations $RD^{proc}_{i,j,t}$ and the second part by a knowledge stock for product innovations $RD^{prod}_{i,j,t}$, both depending on the company i, the technology j and the time period t.

Both stock variables can be increased either by own investments in R&D ($I^{proc}_{i,j,t}$ or $I^{prod}_{i,j,t}$) or by knowledge spillover ($SP^{proc}_{i,j,t}$ or $SP^{prod}_{i,j,t}$), where investments in R&D and spillover are understood as perfect substitutes. The build-up of a knowledge stock for innovations has the property that it is a time consuming process where experiments and knowledge is step by step accumulated over time. It is also assumed, that the return to investment, measured by increases in the knowledge stock, decreases as the company approaches the frontier of RD_j^{max}. The knowledge starts at zero or at an initialized number in the interval [0,1]. Afterwards the knowledge stock is updated as follows:

$$RD_{i,j,t}^{proc} = RD_j^{max} - \left(RD_j^{max} - RD_{i,j,t-1}^{proc}\right) \frac{1 + \alpha_i \beta_i (I_{i,j,t-1}^{proc} + SP_{i,j,t}^{proc})}{1 + \alpha_i (I_{i,j,t-1}^{proc} + SP_{i,j,t}^{proc})} \tag{1}$$

Here $\alpha_i > 0$ and $\beta_i > 0$ are firm-specific parameters, which describe the ability of the firm to develop new products and the efficiency of the use of R&D funds. In particular, firm i can each period reduce the gap to the frontier RD_j^{max} at most by the factor β_i. Equation (1) also represents the cumulative property of knowledge. A rising knowledge stock for process innovations $RD_{i,j,t}^{proc}$ leads directly to lower production cost.

The formula for updating the knowledge stock for product innovations is similar with the only difference, that the upper bound is equal to 1:

$$RD_{i,j,t}^{prod} = 1 - \left(1 - RD_{i,j,t-1}^{prod}\right) \frac{1 + \alpha_i \beta_i (I_{i,j,t-1}^{prod} + SP_{i,j,t}^{prod})}{1 + \alpha_i (I_{i,j,t-1}^{prod} + SP_{i,j,t}^{prod})} \tag{2}$$

In contrast to process innovation a knowledge stock for product innovation greater zero does not automatically lead towards a successful product innovation. In fact the immanent uncertainty with product innovations is captured by a stochastic process which determines, if a product innovation is successful or not. A product innovation can be either incremental or radical.[2] In case of a radical innovation a new technology was created which is a little more separated from the others. In order to show this we have to introduce the technology space first.

[2]Two numbers were chosen: u from the uniformly distributed interval $[c, d]$ with $0 < c < d$, and v from the uniformly distributed interval $[d, e]$ with $d < e \leq 1$. If $RD_{i,j,t}^{prod} > u$ the firm i was able to introduce a product innovation on the market. If $RD_{i,j,t}^{prod} > v$ the new product was a technological breakthrough, which could be interpreted as a radical innovation. Otherwise the product innovation is incremental.

2.2 The Technology Space

The technology space is interpreted as a circle in tradition of the circular city models in the industrial organization literature (originally introduced by Salop, 1979). The idea is that products belonging to a technology j, which marks a certain point on that circle, are horizontally differentiated. The technological distance $d^{tech}_{j,j+1,t}$ between two technologies j and $j+1$ is interpreted as the shortest way on the circle. The overall number of existing technologies should be m_t. In figure 1 the technological space and the corresponding technological distances are shown.

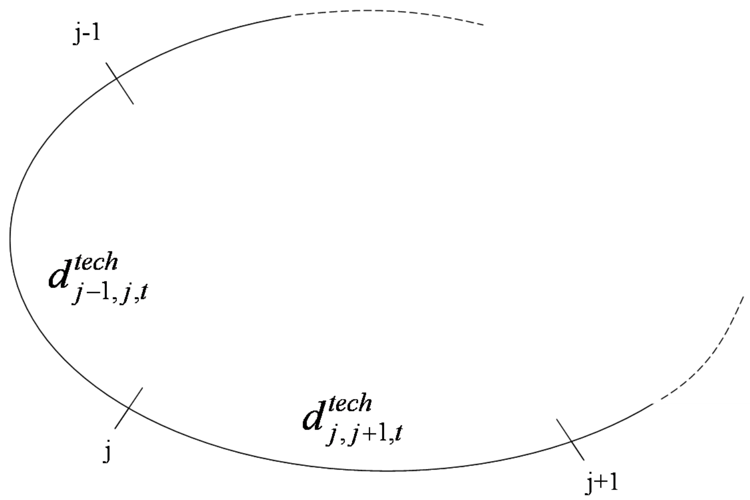

Figure 1: The technology space as a circle.

A successful product innovation adds a new technology on the circular technology space. In the case of incremental innovation the new technology $m_t + 1$ is placed right in the middle between two existing ones. The firm wants to get close to a promising technology j but while all products are substitutes, it chooses j as a neighbor but as far as possible. The firm will choose a technological location next to j where the technological distance to the next technology is greatest. If the technological distances to the neighbors are equal, the firm will choose a location with a higher starting value for the knowledge stock for process innovation.[3]

[3] Thus the new technology will have the technological distance of $d^{tech}_{j,m_t+1,t} = d^{tech}_{m_t+1,j+1,t} = \frac{d^{tech}_{j,j+1,t-1}}{2}$ to their neighbors.

In figure 2 an incremental innovation is illustrated.

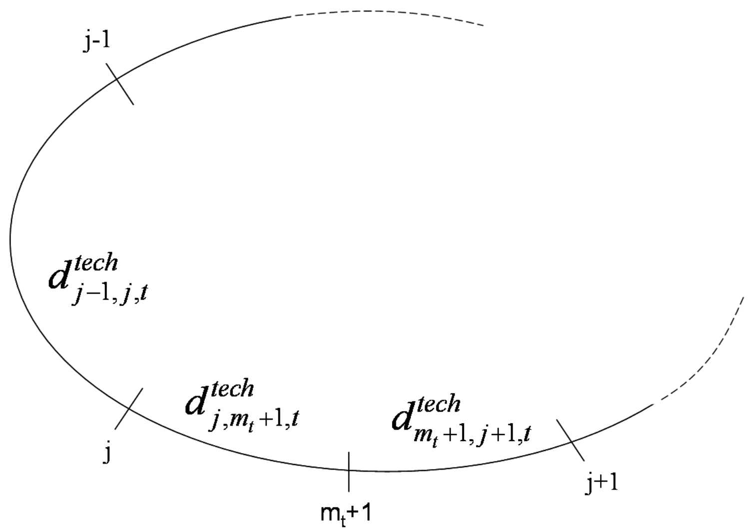

Figure 2: Incremental product innovation.

In the case of a radical innovation the circle expands as the new product adds significant new features to the product of the industry as shown in figure 3. As with every product innovation the firm will always choose a location where the distance to their neighbors is greatest (if equal with the higher starting value for the knowledge stock for process innovations) but in the neighborhood of a specified technology j.[4] For τ periods both connections exist, but afterwards the connection between j and $j+1$ is only possible over the new technology m_t+1. The old connection $d^{tech}_{j,j+1,t}$ is cleared.

The innovating firm with a new kind of product stays for τ periods as a monopolist on this new market. After that period other firms can gain specific knowledge in this technology and produce this product variant, too. The initial R&D stock for this new product variant is depending on the knowledge of the innovating firm in the neighboring technologies. This fact considers the cumulative structure of knowledge, so that the firm can make use of similar knowledge already accumulated in the firm. Thus the initial knowledge stock for the new

[4] In case of a radical innovation the distances to the neighbors stay the same $d^{tech}_{j,m_t+1,t} = d^{tech}_{m_t+1,j+1,t} = d^{tech}_{j,j+1,t-\tau}$.

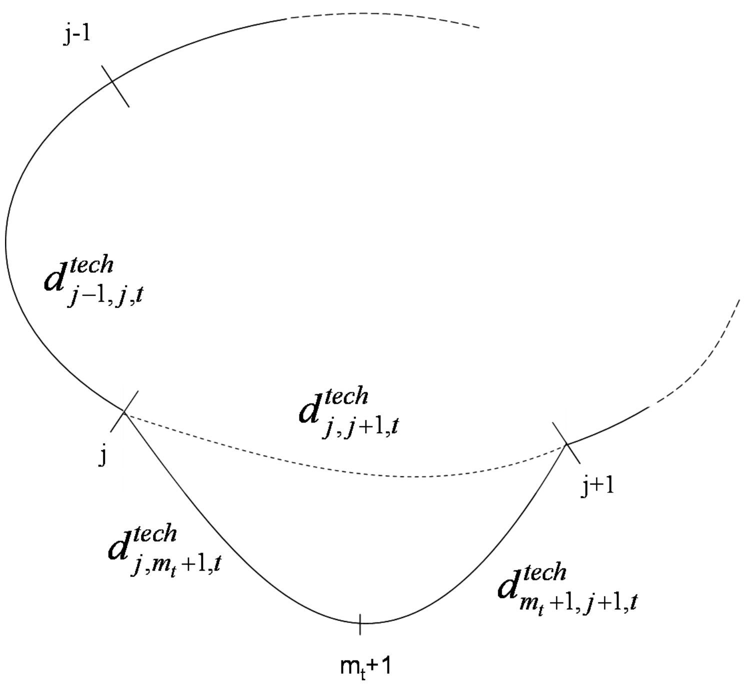

Figure 3: Radical product innovation. (After τ periods the connection $d^{tech}_{j,j+1,t}$ is cleared.)

technology $RD^{proc}_{i,m_t+1,t}$ is the mean of the neighboring technologies of the innovating firm i, but at least a lower bound RD^0 and at most 1.

The maximal value RD^{max}_j which can be reached in this market should be twice this initial knowledge stock for the new technology. This means that the knowledge in every market can only be doubled. If the frontier was reached, firms may try to launch product innovations technological close to this market in order to become experts in that part of the technological space.

An example for the technology space comes from the automobile industry: starting with three main technologies freight vehicles, passenger cars and busses, the introduction of vans and SUVs (sport-utility vehicles) could be interpreted as product innovations. In figure 4 the example is represented. Vans are indicated as an incremental innovation which combines features of the neighboring industries for busses and passenger cars. SUVs could stand for a mixture between passenger cars and freight vehicles. The presentation of SUV with help of marketing instruments was a huge economic profit for the automobile industry. For this, SUVs should be considered (at least in economic perspective) as a radical product innovation. The widening of the technology space leads in total to higher profits for the firms as new consumer groups became interested in products of this industry. A more detailed technological space could be imagined by sorting brands or design models of the automotive industry on the circle.

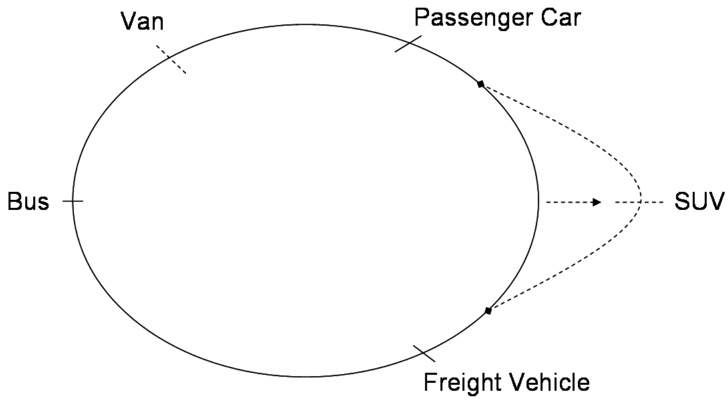

Figure 4: The technology space and an example from the automobile industry.

2.3 Learning through Knowledge Spillover

Heterogeneity of knowledge is a precondition for learning. The differences in knowledge are interpreted in two ways: First, there are technological distances between different strands of technologies. Second, there is a difference in two knowledge stocks which represents the knowledge gap. The knowledge gap $t_{ik,jl,t}$ between firm i an k related to different technologies j and l in period t is:

$$t_{ik,jl,t} = \max\left\{\ln\left(\frac{RD^{proc}_{k,l,t}}{RD^{proc}_{i,j,t}}\right), 0\right\}$$

In this formula the technological gap is only greater than zero, if the other company k has a greater value of the knowledge stock variable. The function is concave.

As mentioned above the absorptive capacity of a firm is crucial for learning through knowledge externalities. The concept of absorptive capacity is incorporated in the variable $\gamma_{i,t}$ of firm i in t, which is assumed to be the mean value over all m_t technologies. Therefore a firm with a high amount of technological knowledge is able to absorb a higher fraction of external and internal knowledge:

$$\gamma_{i,t} = \frac{\sum_j^{m_t} RD_{i,j,t}^{proc}}{m_t}$$

Up to now we presented the technological aspects of proximity and learning. The geographical aspect of learning is captured by the geographical distance $d_{i,t}^{geo}$ of firm i. The geographical distance is modelled similar to core periphery models (see e.g. Krugman, 1991). There are only two possible locations for firms: in the core (or cluster) or outside in the periphery.

$$d_{i,t}^{geo} = \begin{cases} 0, & \text{in the core;} \\ 1, & \text{in the periphery.} \end{cases}$$

A location in the core leads to a better exchange of tacit knowledge but it might also raise the own production cost because of scarce resources through higher office rents or price for building land, higher wages for employees etc. If a company is a technological leader it might also prefer a location in the periphery in order not to let too much knowledge spill over upon competitors.

Now we do have all ingredients for the calculation of knowledge spillover which represent learning in the model. Firms i and k can learn from competitors only if both of them are placed in the core, that is $(1 - d_{i,t}^{geo}) \cdot (1 - d_{k,t}^{geo}) = 1$. But learning can also happen within the firm, where knowledge is transmitted from one kind to another. Learning regards all technologies m_t. Based on the formula for knowledge spillover from Verspagen (1993) and Cantner and Pyka (1998a,b) with two kinds of distances $d_{i,t}^{geo}$ and $d_{j,l,t}^{tech}$, the technological gap $t_{ik,jlt}$ and the absorptive capacity $\gamma_{i,t}$ the resulting knowledge spillover for process innovations $SP_{i,j,t}^{proc}$ for the technology j and firm i can be written as:

$$\begin{aligned} SP_{i,j,t}^{proc} = & \sum_{l=1}^{m_t} \sum_{k \neq i} \left[(1 - d_{i,t}^{geo})(1 - d_{k,t}^{geo}) \cdot \frac{1}{1 + d_{j,l,t}^{tech}} \cdot t_{ik,jl,t} \cdot e^{-\frac{t_{ik,jl,t}}{\gamma_{i,t}}} \right] \\ & + \sum_{l=1}^{m_t} \left[\frac{1}{1 + d_{j,l,t}^{tech}} \cdot t_{ii,jl,t} \cdot e^{-\frac{t_{ii,jl,t}}{\gamma_{i,t}}} \right] \end{aligned} \tag{3}$$

Analogously the knowledge spillover for product innovations $SP_{i,j,t}^{prod}$ are formulated.

The first term stands for the external knowledge spillover. They are only greater than zero if both firms are in the core. The second term stands for internal knowledge spillover which exist independent of the geographical location of the firm. The formula is build in that way, that it is maximized if the technological gap equals the absorptive capacity. Any deviations from this point lead to lower knowledge transfer. This represents that learning has less effect if the knowledge is too similar or too different. A higher technological distance $d_{j,l,t}^{tech}$ between the two regarding technologies j and l reduces the possible learning effect, too.

Learning in this model is therefore described in that way that the technological profiles of two firms are compared and the specific gains are calculated. Even with no own investments in R&D firms could increase their specific knowledge by learning.

2.4 Market Demand

We consider an industry consisting of n producers. At any point in time t there exist m_t sub-markets within this industry, where each sub-market represents a variant of the product considered. With every technology located on the circular technological space the production of a certain variant is possible. Thus the index j stands for each sub-market as well for the corresponding technology. Consumers are assumed to have love-for-variety preferences where the representative consumer has a utility function:

$$u_t\left(X_{1t}..X_{m_t t}\right) = \left[\sum_{j=1}^{m_t}\left(A_{j,t}\cdot X_{j,t}\right)^b\right]^{1/b} \tag{4}$$

The parameters $A_{j,t}$ denote the current attractiveness of product variant j and $X_{j,t}$ consumption of product variant j. The degree of complementarity between the different product variants is expressed by $b \in [0,1]$ where values close to zero correspond to complementary goods whereas the variants are perfect substitutes for $b = 1$.

The standard love-for-variety approach assumes equal attractiveness of the variants but in this case the variants should be weighted by the level of attractiveness. The attractiveness $A_{j,t}$ of product variant j depends on the technological distances to the neighbors of j in the technology space. The greater the product of the distances the greater is the market niche and therefore the attractiveness for the consumers:

$$A_{j,t} = d^{tech}_{j-1,j,t} \cdot d^{tech}_{j,j+1,t} \tag{5}$$

The utility function in equation (4) is maximized subject to the budget constraint:

$$\sum_{j=1}^{m_t} p_{j,t} \cdot X_{j,t} \leq B(t) \tag{6}$$

$B(t)$ denotes the overall amount of money allocated by consumers to purchase goods produced in this industry. We will assume that it increases with the number of attractiveness of product variants, however at a decreasing rate:

$$B(t) = msize \frac{m_t}{A + m_t} \tag{7}$$

Here $msize$ gives the maximal amount of money that could be allocated to purchase in this industry and A governs how fast the allocated funds grow with increasing overall attractiveness of the sub-markets. By making this assumption we intend to capture the goods produced in this industry do not only compete among themselves but also compete for consumer budget allocation with outside products. All producers in this industry set production quantities for all sub-markets they are in and prices are determined by market clearing. Straightforward calculations yield the following inverse demand curve for a market j:

$$p_{j,t} = \frac{B(t) \cdot A^b_{j,t}}{X^{1-b}_{j,t} \cdot \sum_{l=1}^{m_t} \left(A_{l,t} \cdot X_{l,t}\right)^b} \tag{8}$$

In contrast to Dawid and Reimann (2003, 2004) in this model no explicit industry life cycle via the attractiveness of the product variants is incorporated. In this model there will be a reduction in demand on one sub-market with increasing number of product innovations. But the demand of one sub-market will however never fall down to zero.

2.5 The Cost Structures of Producers

Each of the n firms in the industry can in every period produce for each of the public sub-markets. We denote by $M_{i,t}$ the set of markets the firm i produces for in period t and by $x_{i,j,t}$ the output quantity of firm i on sub-market j. The firms production cost are given by:

$$C_{i,t}(x_{i,t}) = F_i \cdot |M_{i,t}| + \sum_{j \in M_{i,t}} (\overline{c}_{i,j,t} \cdot x_{i,j,t}^2) \tag{9}$$

The fixed cost F_i are a constant firm specific parameter. For every sub-market the firm produces for fix cost F_i arise. The variable costs $\overline{c}_{i,j,t}$ depend on two factors: first the amount of knowledge in technology j and geographical location of the firm, because we assume that all production takes place at the location of the firm. The first term $c_{i,j,t}$ is in consequence depending on the current knowledge and the second term depends on the geographical location:

$$\overline{c}_{i,j,t} = c_{i,j,t} + c_t^{geo} \tag{10}$$

An important aspect of this model is the fact that production cost can be decreased over time through process improvements and accumulation of tacit knowledge. The variable $c_{i,j,t}$ is a result of such process improvements. At the time where firm i starts producing variant j we have $c_{i,j,t} = c_{i,j}^{ini}$ but afterwards i can invest in every period t where $j \in M_{i,t}$ in cost reducing process improvements in the production of j. We assume that there is a maximal fraction $(1 - c_{i,j}^{min})$ by which this cost parameter can be reduced through the knowledge stock for process innovations $RD_{i,j,t}^{proc}$. As written above the knowledge stock can be increased by investments in R&D or by knowledge spillover.

$$c_{i,j,t} = c_{i,j}^{ini} \left[c_{i,j}^{min} + (1 - c_{i,j}^{min})(1 - RD_{i,j,t}^{proc}) \right] \tag{11}$$

The scarce resource in the core leads to an increase in the marginal production cost of every firm in the core. If only one firm is in the core no additional cost will occur. The marginal cost for every single output quantity of a firm in the core ($d_{i,t}^{geo} = 0$) is increased by c_t^{geo}. How much the production cost raise depends on the total number of firms in the core and on the parameters R and c^{geo}.

$$c_t^{geo} = (1 - d_{i,t}^{geo}) \cdot (|N_t| - 1)^{c^{geo}} \cdot R \tag{12}$$

The number of firms in the core should be called $|N_t|$, where N_t is the set of firms which are located in period t inside the core. The parameter c^{geo} describes the gradient of the geographical cost function, for example $c^{geo} < 1$ would lead to a concave and $c^{geo} > 1$ to a convex geographical cost function.

In result two counter effects arise inside the core. On the one hand a firm can profit from learning through knowledge spillover, which reduce via process innovations the term $c_{i,j,t}$. But on the other hand the firm has higher marginal cost because of the scarce resource.

2.6 Decision Making

The decision process of the firms involves three steps: first, to decide on the set of markets the firm intends to service, second to determine the output quantities for these markets, and third to decide on investments in product or process innovations and geographical location.

The firms behavior is based on decision rules in the tradition of evolutionary modelling (Nelson and Winter, 1982). Firms have different forms of evaluating technologies, sub markets and location. Depending on this evaluation they will enter and exit sub markets, invest in product and process innovations or change their location from core to periphery or vice versa.

2.6.1 Market Entry and Exit

The total number of firms in the industry n is assumed to stay constant. But the number of firms who are active on a certain sub-market is determined endogenous. The change in the market portfolio a firm holds is modelled as a sequence of rule-based market exit and entry decisions. The exit and entry rules rely on an evaluation of all existing markets carried out at the beginning of each period. It is assumed that at the end of period all firms can observe the average profits on every market and have an idea of the public technology space.

In order to keep the model as simple as possible the evaluation for market entry depends only on the average profits on a sub-market and on the technological distance to the own main technological focus. The factors in the evaluation function should be in the interval $[0, 1]$. For this the average profit $\bar{\Pi}_{i,j,t-1}$ on the market j is divided by the greatest profit a firm made on any sub-market in the last period.

The own technological focus l is the technology with the greatest knowledge stock: l from $\max_j \{RD^{proc}_{i,j,t}\}$. For this the evaluation $v_{i,j,t}$ of a sub-market j is given by:

$$v_{i,j,t} = \left(\frac{\bar{\Pi}_{i,j,t-1}}{\max_{k,l}\{\Pi_{k,l,t-1}\}}\right)^{\frac{\delta_{i,\Pi}}{\delta_{i,\Pi}+\delta_{i,T}}} \cdot \left(\frac{1}{1+d^{tech}_{j,l,t}}\right)^{\frac{\delta_{i,T}}{\delta_{iT}+\delta_{i,\Pi}}} \qquad (13)$$

The sum of the exponents is chosen to be equal to 1. The exponents are important parameters of the firm's diversification strategy since they represent the weights assigned to profits and technological specialization.

To make the entry decision the firm ranks all available markets[5] it does not currently serve according to their evaluations and determines the best existing non-served market as the entry candidate. The entry candidate is added to the portfolio if $v_{i,l,t} > \kappa_{i,en}$. The parameter $\kappa_{i,en} > 0$ is an inertia parameter and represents the aggressiveness of the firm's entry policy. The firm can only enter in one sub-market every period.

The exit decision of the firm is determined solely on the sum of profits of the last τ_{ex} periods. The firm will chose the market with lowest value for $\sum_{\tau=1}^{\tau_{ex}} \Pi_{i,j,t-\tau}$ and will exit this sub-market if the sum of the profits is negative: $\sum_{\tau=1}^{\tau_{ex}} \Pi_{i,j,t-\tau} < 0$. The knowledge of this specific technology remains in the firm. The firm exits up to one sub-market a period.

2.6.2 Quantity Decisions

In order to describe the rules which govern the quantity decision making of the firm we should first be more explicit about the amount of information firms can use. We assume that the aggregate output quantities and the number of firms in all sub-markets at $t-1$ can be observed by all producers including those that were not active in this market. Furthermore, the price elasticities of demand $\epsilon_{j,t}$ for these quantities are also common knowledge. Each firm has in all periods perfect information about the own fixed cost F_i and marginal cost $\bar{c}_{i,j,t}$ of production of

[5] After a successful product innovation the innovating firm is monopolist on this market for τ periods and therefore no other firms can enter.

all product variants. Firms however do not have perfect information about the exact shape of entire demand function and also do not know other firm's cost structures.

Given the set of sub-markets $M_{i,t}$ firm i tries to maximize their profits by choosing the optimal output quantity $x_{i,j,t}$ in each sub-market:

$$\max_{x_{i,j,t}, j \in M_{i,t}} \left[p_{j,t} \cdot x_{i,j,t} - \overline{c}_{i,j,t} \cdot x_{i,j,t}^2 \right] \tag{14}$$

subject to the constraint that current production has to be paid for by the current stock of savings:

$$S_{i,t} \geq F_i \cdot |M_{i,t}| + \sum_{j \in M_{i,t}} (\overline{c}_{i,j,t} \cdot x_{i,j,t}^2). \tag{15}$$

The corresponding fist order conditions with the lagrange multiplier $\mu_{i,t} \geq 0$ of the firm's budget constraint and $MR_{i,j,t}$ the marginal revenue are:

$$p_{j,t} + x_{i,j,t} \cdot \frac{\delta p_{j,t}}{\delta x_{i,j,t}} - 2 \cdot \overline{c}_{i,j,t} \cdot x_{i,j,t} - \mu_{i,t} \cdot 2\overline{c}_{i,j,t} \cdot x_{i,j,t} =$$

$$MR_{i,j,t} - 2(1 + \mu_{i,t})\overline{c}_{i,j,t} \cdot x_{i,j,t} = 0 \quad \forall j \in M_{i,t} \tag{16}$$

Due to the limited information about the demand function and the competitor's production cost, firms cannot simply determine the Nash equilibrium of this quantity setting game. Rather they use some heuristic approximations to determine their output quantity. For setting the quantity output several steps have to be taken.

First, the firms believe that all producers in the sub market j change their output quantity by the same factor λ_j. For this the total estimated output $\hat{X}_{j,t}$ on sub market j is given by: $\hat{X}_{j,t} = \lambda_j \cdot X_{j,t-1}$. Second, the firms assume that the price elasticities are constant: $\hat{\epsilon_{j,t}} = \epsilon_{j,t-1}$. Third, the firms expect that all firms change their output in the same way they would do: $\hat{\lambda_j} = \lambda_{i,j,t}$. Thus they expect the following prices:

$$\hat{p}_{j,t} = p_{j,t-1} \left(1 + \frac{\lambda_j - 1}{\epsilon_{j,t-1}} \right)$$

At last, the firms approximate their marginal revenue by the following expression typically used in standard markup pricing formulas:

$$M\hat{R}_{i,j,t} = \hat{p}_{j,t}\left(1 + \frac{x_{i,j,t}}{\hat{X}_{j,t}\cdot\epsilon_{j,t-1}}\right)$$

With these information the firms can calculate their optimal production quantity in each sub-market. For firms that have been in sub-market j in period $t-1$ inserting these expression into (16) gives the output quantity $x_{i,j,t} = \lambda_{i,j,t}\cdot x_{i,j,t-1}$, where:

$$\lambda_{i,j,t} = \frac{p_{j,t-1}(\epsilon_{j,t-1}-1)(X_{j,t-1}\epsilon_{j,t-1}+x_{i,j,t-1})}{2\overline{c}_{i,j,t}(1+\mu_{i,t})x_{i,j,t-1}X_{j,t-1}\epsilon_{j,t-1}^2 - p_{j,t-1}(X_{j,t-1}\epsilon_{j,t-1}+x_{i,j,t-1})} \tag{17}$$

It becomes obvious from this expression that the actual rates of changes are heterogenous.

A firm which did not produce variant j in period $t-1$ but added this sub-market in t first tries to estimate the change of output quantity of the incumbents and determines its optimal quantity based on this. The expected rate of change of output of the incumbents in the market is determined analogous to (17) where $x_{i,j,t-1}$ is replaced by the average output of a producer of variant j in period $t-1$. $N_{j,t-1}$ should be the set of producers in the sub-market j in the period $t-1$.

$$x_{i,j,t-1} = \frac{\sum_{k\in N_{j,t-1}} x_{k,j,t-1}}{|N_{j,t-1}|}$$

The expectations of firm i about total output in t in such a case is $\hat{X}_{j,t} = \lambda_{i,j,t}\cdot X_{j,t-1} + x_{i,j,t}$. Inserting into (16) implies a production quantity of:

$$x_{i,j,t} = \frac{X_{j,t-1}p_{j,t-1}(\epsilon_{j,t-1}-1)\left[\epsilon_{j,t-1}(|N_{j,t-1}|-1)+\sqrt{\epsilon_{j,t-1}(\epsilon_{j,t-1}(|N_{j,t-1}|+1)^2+4)}\right]}{2\left[p_{j,t-1}(\epsilon_{j,t-1}|N_{j,t-1}|+1) - 2\overline{c}_{i,j,t}X_{j,t-1}\epsilon_{j,t-1}^2(1+\mu_{i,t})\right]} \tag{18}$$

Finally there is a minimum quantity $x_{min} > 0$ which has to be produced by any firm which decided to keep this sub-market in its portfolio. If the result of the quantity calculations is below this level the firm still produces x_{min}. Also in the initial period and every time when a sub-market is founded the quantity x_{min} is produced by the founder.

2.6.3 Investments in Geographical Location

Starting from a random location the firms may decide to change their geographical location from core ($d_{i,t}^{geo} = 0$) to periphery ($d_{i,t}^{geo} = 1$) or vice versa. The shifting of the location leads to the sunk cost c_{fix}^{geo} due to expenses for transferring the production and R&D facilities. These costs are constant in order to keep the model simple. The investments occur when a location is changed:

$$I_{i,t}^{geo} = \begin{cases} c_{fix}^{geo}, & \text{if } d_{i,j,t}^{geo} \neq d_{i,j,t+1}^{geo}; \\ 0, & \text{otherwise.} \end{cases}$$

For the evaluation of the two location alternatives three factors seem to be important. First, the production costs inside the core increase because of a scarce resource. Second, the main advantage of a headquarter inside the core lies in the learning effect through spatially transferred knowledge. But knowledge spillover are a threat for the own core competence in knowledge. For this a third point aims at the own technological leadership.

Because knowledge for product innovations is only a first step to form a technological advantage, the knowledge stock for process innovation $RD_{i,j,t}^{proc}$ (and the corresponding spillover $SP_{i,j,t}^{proc}$) is the main indicator for a knowledge competence. Thus for the evaluation of the location only this knowledge is considered.

The evaluation for the geographical location $v_{i,t}^{geo}$ of firm i lies in the interval $[0, 1]$, where a result of 1 stands for a strong incentive to set the headquarter of the company inside the core. $M_{i,t}$ is the set of sub-markets of firm i in period t. A market j is in the set $R_{i,t}$ if the potential knowledge spillover are greater than zero: $SP_{i,j,t}^{proc}(d_{i,t}^{geo} = 0) > 0$. The evaluation function can be written as:

$$\begin{aligned} v_{i,t}^{geo} = & \left(\frac{1}{|M_{i,t}|} \sum_{j \in M_{i,t}} \frac{\overline{c}_{i,j,t}(d_{i,t}^{geo} = 1)}{\overline{c}_{i,j,t}(d_{i,t}^{geo} = 0)} \right)^{\frac{\delta_{i,R}}{\delta_{i,R}+\delta_{i,RD}+\delta_{i,SP}}} \\ & \cdot \left(1 - \frac{1}{|R_{i,t}|} \sum_{j \in R_{i,t}} \frac{SP_{i,j,t}^{proc}(d_{i,j,t}^{geo} = 1)}{SP_{i,j,t}^{proc}(d_{i,j,t}^{geo} = 0)} \right)^{\frac{\delta_{i,SP}}{\delta_{i,R}+\delta_{i,RD}+\delta_{i,SP}}} \\ & \cdot \left(1 - \frac{1}{|M_{i,t}|} \sum_{j \in M_{i,t}} \frac{RD_{i,j,t}^{proc}}{RD_{j,t}^{proc}} \right)^{\frac{\delta_{i,RD}}{\delta_{i,R}+\delta_{i,RD}+\delta_{i,SP}}} \end{aligned} \qquad (19)$$

As mentioned above the first term considers the marginal production costs depending on the geographical location. If no other firm chooses their location inside the core, the term would become 1. The first term decreases as the number of firms inside the core increases.

The second term describes the effect of the knowledge spillover. The numerator is the sum of the internal knowledge spillover which would occur in every location. The denominator is the sum of the internal and external spillover. If a firm profits a lot from the external spillover, the firm would have an incentive to go inside the cluster.

The last term takes acknowledge of the possible loss of a technological core competence. Hereby the firm's i knowledge is divided by the maximum knowledge of another firm in this market where $RD_{j,t}^{proc} = \max_i \{RD_{i,j,t}^{proc}\}$. If the potential loss is great the firm would have the incentive to choose a location far away from the other firms, or one minus this term promotes a location in the core.

Like in the evaluation function of market entry, see (13), the firm specific parameters $\delta_{i,R}$, $\delta_{i,RD}$ and $\delta_{i,SP}$ represent the firm strategy. The parameters weight the different terms such that heterogenous firm strategies can be reproduced. As in the evaluation of markets there exists an inertia parameter $\kappa_{i,S}$.

If firm i has a location in the periphery ($d_{i,j,t}^{geo} = 1$), the firm will choose their geographical distance for the next period as following:

$$d_{i,t+1}^{geo} = \begin{cases} 0, & \text{if } v_{i,t}^{geo} > \kappa_{i,S} \wedge S_{i,t} > I_{i,t}^{geo}(d_{i,t+1}^{geo} = 0); \\ 1, & \text{otherwise.} \end{cases}$$

If firm i is inside the core ($d_{i,t}^{geo} = 0$), it will choose their geographical distance for the next period as following:

$$d_{i,t+1}^{geo} = \begin{cases} 1, & \text{if } v_{i,t}^{geo} < \kappa_{i,S} \wedge S_{i,t} > I_{i,t}^{geo}(d_{i,t+1}^{geo} = 1); \\ 0, & \text{otherwise.} \end{cases}$$

In both cases the shift of location has to be funded by the firm's savings $S_{i,t}$. If the firm can not afford this, the firm's location doesn't change.

2.6.4 Investments in Research and Development

At the end of a period each firm decides on its investments in product and process innovations. Both investments $I_{i,j,t}^{proc}$ and $I_{i,j,t}^{prod}$ increase the corresponding knowledge stocks $RD^{proc}_{i,j,t}$ respectively $RD^{prod}_{i,j,t}$. The R&D investment quota for product innovation is denoted by q^{prod}_i and the quota for process innovation is q^{proc}_i.

$$I^{prod}_{i,j,t} = q^{prod}_i \cdot \Pi_{i,t}$$
$$\sum_j I^{proc}_{i,j,t} = q^{proc}_i \cdot \Pi_{i,t}$$

Since process investments lead to a reduction of per unit cost of production the firm allocates these funds to the different sub-markets proportional to an adjusted expression of its current output in each market.

$$I^{proc}_{i,j,t} = q^{proc}_i \cdot \Pi_{i,t} \cdot \frac{x_{i,j,t}}{\sum_{k \in M_{i,t}} x_{i,k,t}}$$

A product innovation is seen as an alternative to market entry: in order to extract rents on a profitable market a new market next to the existing one is founded. For this the evaluation function for product innovations is is equal to the evaluation of markets, see (13). The only difference is that now all markets are considered, whereas the decision for market entry took only those markets into account, which were not served by the firm i.

$$v^{prod}_{i,j,t} = v_{i,j,t} = \left(\frac{\bar{\Pi}_{i,j,t}}{\max_{k,l}\{\Pi_{k,l,t}\}} \right)^{\frac{\delta_{i,\Pi}}{\delta_{i,\Pi}+\delta_{i,T}}} \cdot \left(\frac{1}{1 + d^{tech}_{j,l,t}} \right)^{\frac{\delta_{i,T}}{\delta_{iT}+\delta_{i,\Pi}}} \tag{20}$$

The firm i will invest all his expenditures for product innovations in the market l with the highest evaluation (but only if $v^{prod}_{i,j,t} > 0$): $I^{prod}_{i,l,t} = q^{prod}_i \cdot \Pi_{i,t}$.

2.7 Market Clearing

With all given quantity outputs $x_{i,j,t}$ prices and price elasticities can be calculated for all sub-markets. The price for each sub-market is given by expression (8) and the price elasticity of demand can be calculated from the price function. With the given cost functions every firm is able to derive their profit $\Pi_{i,j,t}$ on every sub-market as well as their overall profit $\Pi_{i,t}$:

$$\Pi_{i,j,t} = \left(x_{i,j,t} \cdot p_{j,t} - F_i - \bar{c}_{i,j,t} \cdot x^2_{i,j,t} \right) \tag{21}$$
$$\Pi_{i,t} = \sum_{j \in M_{i,t}} \Pi_{i,j,t} \tag{22}$$

All firms start with initial Savings of S^0. They can also take debts up to the same level. Every period they earn total profit $\Pi_{i,t}$ but also have to make their investments on process innovations $I^{proc}_{i,j,t}$ and product innovation $I^{prod}_{i,j,t}$ and eventually on the change of location $I^{geo}_{i,t}$. The Savings for the next period should be expressed by the following formula while ρ stand for the interest rate:

$$S_{i,t+1} = (1+\rho)S_{i,t} + \Pi_{i,t} - I^{geo}_{i,t} - I^{prod}_{i,j,t} - \sum_{j \in M_{i,t}} I^{proc}_{i,j,t} \tag{23}$$

3 Simulation Setup

The parameters of the simulation model can be found in Appendix A. They were chosen in that way that the model was able to find reasonable and robust results. For some of the parameters a certain range was defined. The results presented in the next section are based on 100 randomly generated profiles which were created while choosing the parameters from the given interval by a given distribution function. With each of these profiles the model runs for $T = 100$ periods. The results of this runs were averaged in order to get the qualitative impact of the parameters.

The model starts every time with a technology space with $m_0 = 5$ technologies, located on a circle with the technological distances of $d^{tech}_0 = 2$ between those technologies. In total the industry consists of $n = 10$ firms which interact on the product markets. The geographical location of these firms is chosen randomly such that in average half of the firms start in the core and the other half in the periphery. Each firm starts with a randomly generated knowledge in one of the technologies and is also an active member of the corresponding sub-market. The starting level is normally distributed around mean RD^0 with the variance σ^2_0. Thus on every sub-market there are exactly two firms active in the first period.

The firm are heterogeneous in their geographical location ($d^{geo}_{i,t}$), specific knowledge ($RD^{proc}_{i,j,t}$, $RD^{prod}_{i,j,t}$), fixed cost (F_i), capabilities to perform R&D (α_i, β_i, q^{prod}_i, q^{proc}_i) and their firm strategies described by the evaluation function ($\kappa_{i,S}$, $\kappa_{i,ex}$, $\kappa_{i,en}$, $\delta_{i,T}$, $\delta_{i,RD}$, $\delta_{i,R}$, $\delta_{i,SP}$, $\delta_{i,\Pi}$).

Firms are able to rent money up to their starting level of savings S^0. If the savings of a firm are less than $-S^0$ the firm is bankrupt. All knowledge of bankrupt firms is lost. Bankrupt firms are replaced in the industry with new starting savings, same knowledge as the technological leader[6] but only in one randomly picked market and random geographical location. The new firm gets new specific parameters which represent the new strategy. Therefore the total number of firms is constant in the industry but the market structure of the sub-markets is determined endogenous.

4 Results of the Simulation Studies

4.1 Observations as the industry evolves

In figure 5 an example for the circular technological space after $T = 100$ periods is given, where the circle is closed in that way that the last technology (17) is neighbor of the first technology (1).

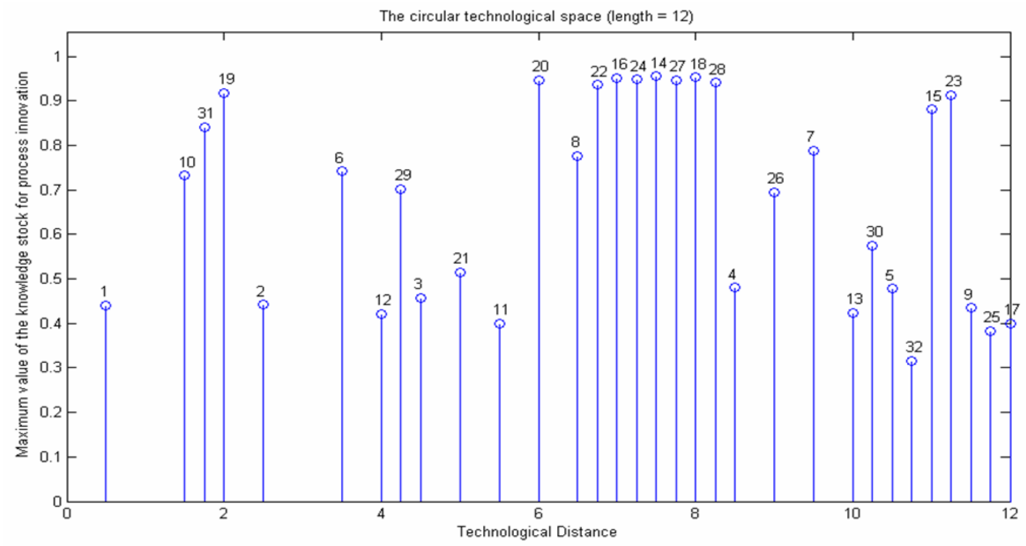

Figure 5: An example of the circular technology space.

The numbers indicate the technologies in their creation order. Each peak stands for a successful product innovation, the height represents the maximum

[6]The substitution of bankrupt firms is understood as an entry of a new firm in this industry The firm would only enter if it has, at least in one technology, the same knowledge as a technological leader.

level of process innovation in that technology.

As written above the industry starts with $m_0 = 5$ technologies with the technological distances of $d_0^{tech} = 2$ between them. Thus the picture shows only one radical product innovation, technology (8), which expanded the length of the circular technological space from 10 to 12. Because of the assumed cumulative structure of knowledge the highest peaks are in technologies with the numbers around 20 but newer technologies would have more potential as the industry would continue to evolve. The technological space may also be drawn for every firm, in this case it would represent the technological profile of this firm.

In order to study the effects of geographical proximity the number of firms in the core is presented with different cost for the scarce resource, see figure 6. All three curves have a similar pattern.

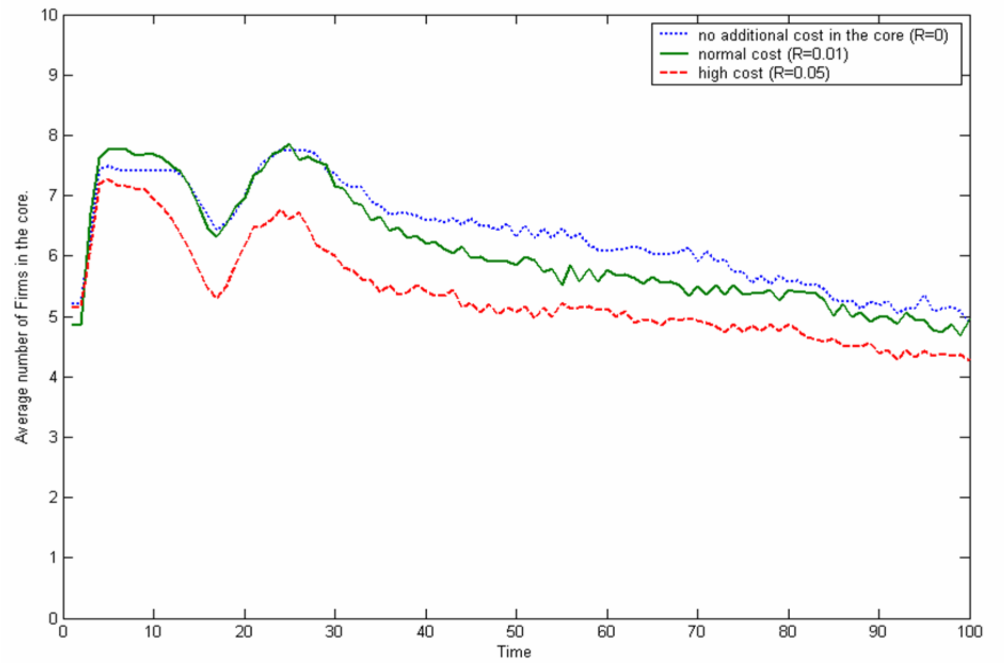

Figure 6: Mean of firms in the core with different cost for scarce resource.

The initial location was chosen randomly and thus in average five firms start in the core. Firms start with knowledge in only one technology. Because no process innovations were introduced at the start, the additional cost in the core compared to other cost are relative low. By assumption two firms have a knowledge stock greater than zero in each technology and hence no firm has a huge technological lead. Because of the mentioned reasons firms have a strong incentive to join the core at the beginning of the simulations. This incentive is reduced in particular after the first introduction of new products around period 20. With successful product innovations the innovating firms become technological leader and try to keep their status by leaving the core. But afterwards firms again decide to participate at the learning processes and enter the core. The relevance of geographical proximity is reduced over the time but in average most of the firms in all cases choose a location close to other firms. This means that a low geographical distance to competitors is important during the developing period of an industry as well as the industry becomes more mature.

In figure 6 three different scenarios were presented: no, normal and high additional cost for scarce resources in the core. It can be seen, that even with no extra cost not all firms join core. The possible loss of knowledge through knowledge spillover could be one reason for voluntary isolation. In case of high cost for the scarce resource these cost are around 50% of the average initial cost with half of the firms in the core.[7] This means that a location in core raises the variable cost for every product quantity in that height. Because of process innovations the relative value even increases. As illustrated in the picture even with these high additional cost most firms choose a location with low geographical distance to their competitors.

The next figure 7 could be interpreted as an industry life cycle (see Klepper, 1996). Here the median of active firms on one of the initial sub-markets (1)-(5) is shown over the simulated time horizon for 100 simulation runs. The sub-markets were chosen because they exist in all periods.

The simulation starts with two active firms on each sub-market. In the following periods there is a high number of entrants in these markets. After a period of stagnation firms leave the sub-markets although they collected a lot of specific knowledge in the corresponding technology and although no explicit industry life cycle was modelled in the demand function. One reason for this behavior could be seen in the upper limit for the knowledge stock for process innovations which

[7] In average the initial cost are $c_{i,j}^{ini} = 0.5$. With $|N_t| = 5$, $c^{geo} = 1.2$ and $R = 0.05$ the geographical cost are $c_t^{geo} = (5-1)^{1.2} \cdot 0.05 = 0.2639$, see equation (12).

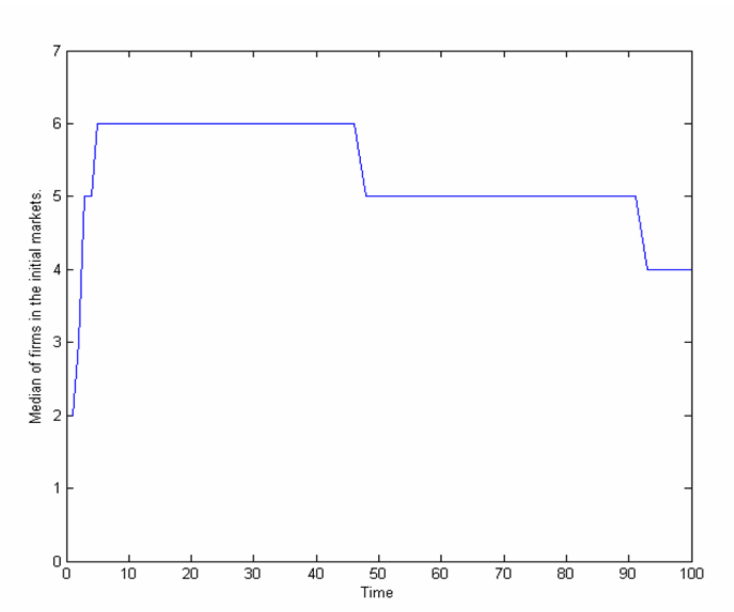

Figure 7: Median of firms in the initial markets.

is low for the initial markets. As the industry evolves a smaller but constant number of firms stay active on each market. Other firms may have knowledge for this particular technology but they do not produce this product variant. A similar behavior was observed after the founding of a new technology which also created a new sub-market.

The presented pattern was observed much clearer in single markets, but the picture shows that is also verifiably on a very high aggregated level.

4.2 Comparison of Different Scenarios

The following analysis is based on four scenarios which differ on the number of firms in the core:

- **0% core:** All firms are always in the periphery. No learning can happen between the firms through knowledge spillover but firms can make use of internal knowledge spillover.
- **50% core:** Half of the firms are located in the periphery, the other half in the core. Firms are not allowed to change their geographical location.

- **variable:** This scenario represents the standard case with the decision rule for changing the geographical location as described in chapter 2.6.3. Firms start with a random location and are free to move as they can afford it. In average about 60% of firms were in the core, therefore this scenario is placed between 50% and 100% core.

- **100% core:** All firms are always in the core. Firms profit from the externalities arising from knowledge spillover but they also might loose their technological lead pretty fast.

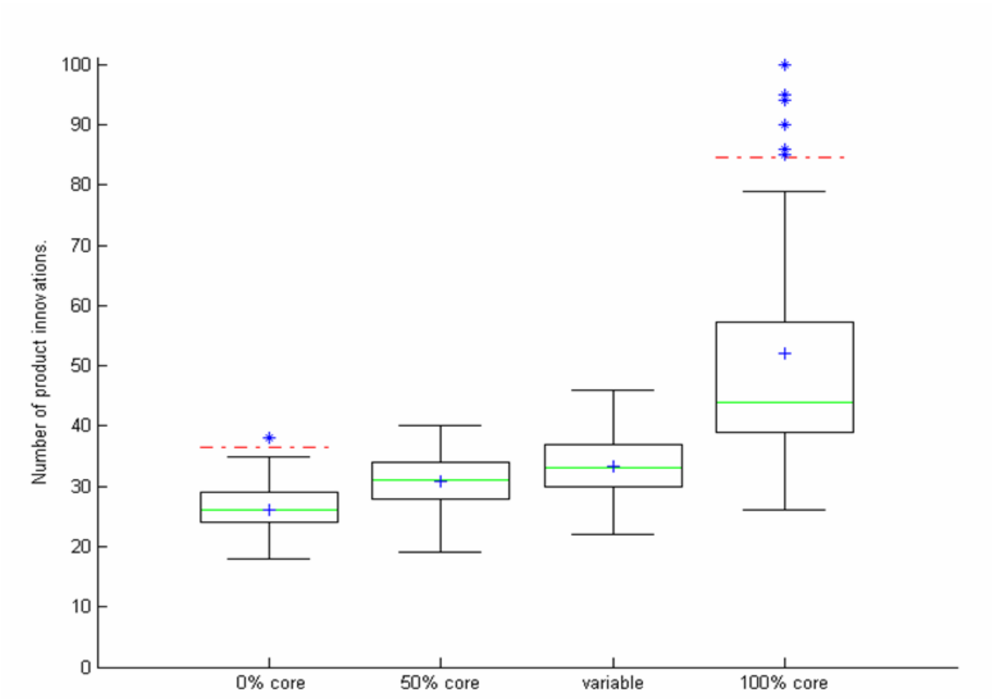

Figure 8: Boxplot of the total number of successful product innovations in different scenarios.

Figure 8 presents boxplots[8] of the total number of product innovations in each simulation run. The total number of product innovations rises sharply as the number of firms in the core increases. Also the variance and the number of upper outliers increased in the case of all firms are always located in the core.

[8]The boxplot function used for presentation was programmed by Ernest E. Rothman.

A statistical test also underline this results (see Appendix B): with a confidence level greater than 99% the null hypothesis, that the mean in scenario variable is equal or greater than the mean in scenario 100% core, can be rejected. It could also be observed that the number of radical product innovation raises with the number of firms which participate at the learning processes, too.

Therefore it can be concluded that the existence of knowledge flows in the core has positive effects on the number of product innovations developed in the industry compared to a scenario where fewer firms are in the core.

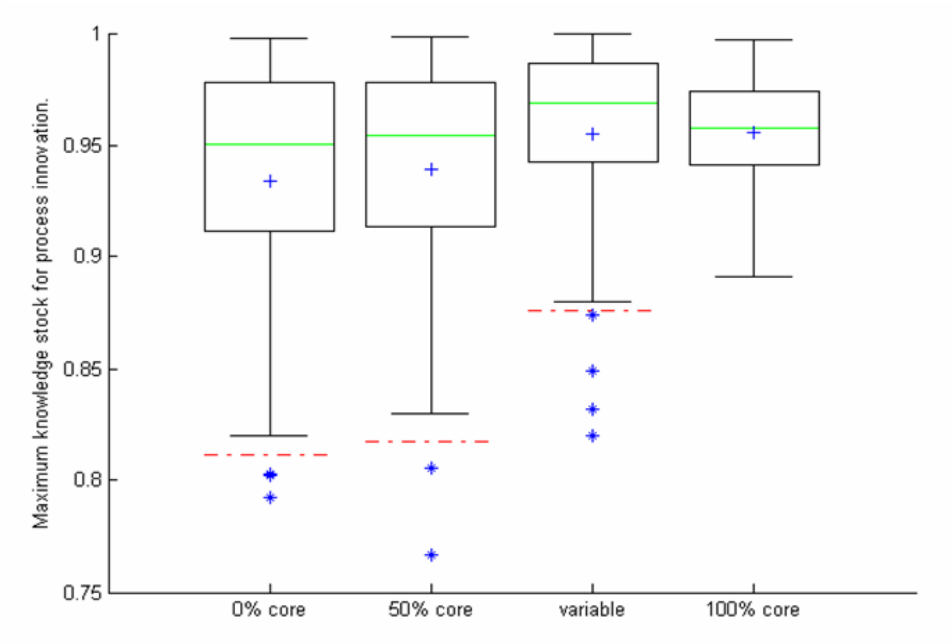

Figure 9: Boxplot of the maximum knowledge stock for process innovation in different scenarios.

The reached level of the knowledge stock for process innovation is presented in figure 9. From this figure two observations can be made: First the variance declines with the number of firms in the core. The upper border of 1 for the knowledge stock could be one reason for the smaller variance. Second the level of the knowledge stock for process innovation seem to reach its maximum in the case with free choice for location. Statistically this proposition can be supported with a confidence level of 90%, see Appendix B.

Surprisingly in contrast to product innovation the maximum level of process innovation in the cases 0% core is not that much lower than in 100% core. The median increases slightly only from 0.9501 in the fist case to 0.9573 in the second case, which is less than 1 percent change.

From this observation it can be deduced that that with fewer product innovations (see figure 8) and no learning between firms almost the same level of process innovation was reached. Only in case of free choice of location the knowledge stock for process innovations was significant higher.

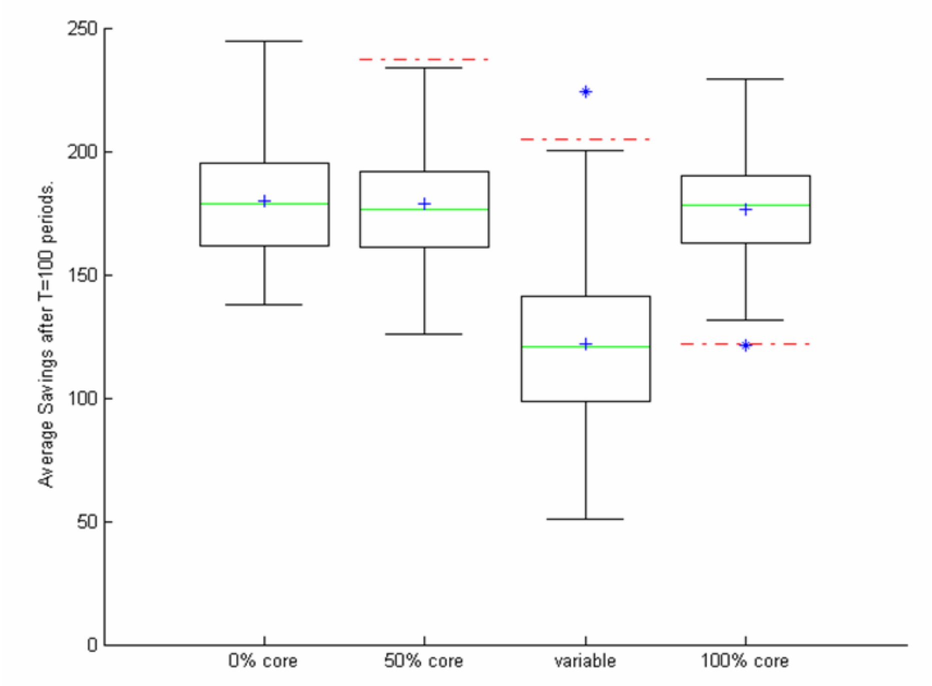

Figure 10: Boxplot of the average level of savings in different scenarios.

The average savings in the case with variable number of firms is smaller than in the case with all firms in the core, see figure 10. One reason for this is that the firm's sunk cost for changing the geographical location are chosen to be very high ($c_{fix}^{geo} = \frac{S^0}{2}$) and therefore reduce savings. It can be shown that with low or no sunk cost firms have the highest level of savings in scenario variable.

In all cases where the firms are not allowed to switch location the savings are about the same level. Thus the average profitability of firms does not depend on the number of firms in the core: the savings in the cases of all firms in the periphery or all firms in the core are more or less equal. A similar result was observed in the case where only half of the firms were in the core. Statistical tests show that with a confidence level greater than 99% the difference of means between the scenarios 0% and 100% core or 50% and 100% core is smaller than 10, see Appendix B.

On the one hand for the profitability of firms the results doesn't change, but on the other hand the technological development, measured in the number of product innovations and maximum level of process innovation, does change with the number of firms in the core. This result could be interpreted as a possible justification for economic policy: as firms are indifferent about all located in the core or all in the periphery, economic policy should try to enforce that all firms are located in the core, because this would lead to a faster technological development of the industry.

5 Conclusions

The paper introduces an agent-based simulation model which considers learning through heterogeneous knowledge spillover. Two factors were discussed in detail: geographical and technological distance and their impact on innovation. The model takes into account that firms differ in their specific knowledge and firm strategy towards market entry and exit, R&D investments and geographical location.

As a first result this model enables the description of the technological development of an industry as well as the evolution of firm specific technological profile. Geographical proximity is important for firms although they have to take into account additional cost of scarce resources. The importance of geographical proximity falls slightly as the industry evolves, but most of the firms still choose to stay inside the core also in a more mature industry. The model generates typical industry life-cycles with respect to the number of firms in each sub-market.

The comparison of different scenarios shows that the average savings of firms are mainly reduced by location changing cost. As the profitability doesn't change in scenarios with all firms in the core or all in the periphery, the number of firms does matter for the technological development of the industry. With an increasing number of firms, which exchange knowledge, the number of product innovations raises sharply. In case of process innovations an increase of the mean and a reduction of the variance could be observed. But the effect is much more clearer with product innovations.

Further examination of the model will concentrate on the aspect of technological distance: What kind of clusters will emerge, technological specialized or diversified? With regard to R&D strategy of firms the question arises, whether it is better to concentrate on the core competence or do firms with more diversified technological profile earn higher profits? How do the incentives for R&D change through heterogenous knowledge spillover: can firms profit from their R&D expenses or are they better off as free riders?

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Appendix

Appendix A: Parameter Setting

Parameter	**Value**
b	0.5
c	0.93
d	0.94
e	0.95
T	100
m_0	5
n	10
A	1
$msize$	100
τ	3
τ_{ex}	3
c^{geo}	1.2
R	0.01
RD^0	0.2
σ_0^2	0.001
d_0^{tech}	2
S^0	10
c_{fix}^{geo}	5
x_{min}	0.1
ρ	0

Table 1: Fixed Parameters

Parameter	**Range**
c_j^{min}	0.2 .. 0.4
c_j^{ini}	0.4 .. 0.6
F_i	0.2 .. 0.4
α_i	3 .. 4
β_i	0.75 .. 0.85
q_i^{proc}	0.08 .. 0.14
q_i^{prod}	0.4 - q_i^{proc}
$\kappa_{i,en}$	0.25 .. 0.75
$\kappa_{i,S}$	0.1 .. 0.5
$\delta_{i,\Pi}$	0.3 .. 0.4
$\delta_{i,SP}$	0.3 .. 0.4
$\delta_{i,R}$	0.3 .. 0.4
$\delta_{i,RD}$	0.3 .. 0.4
$\delta_{i,T}$	0.3 .. 0.4

Table 2: Parameters with range (uniformly distributed in the range if not mentioned different).

Appendix B: Statistical Tests

In order to present statistical analysis a two-sample Wilcoxon rank sum test is used where this test does not assume that the observations come from normal distributions. The alternative hypothesis is formulated and the results of 100 simulation runs are tested.

1. Average number of Product Innovations:
   H0: mean for scenario *variable* $\geq$ mean for scenario *100% core*
   H1: mean for scenario *variable* $<$ mean for scenario *100% core*
   Results: Z = -9.716, p-value = 0

2. Maximum value of the knowledge stock for process innovation:
   H0: mean for scenario *variable* $\leq$ mean for scenario *100% core*
   H1: mean for scenario *variable* $>$ mean for scenario *100% core*
   Results: Z = 1.5711, p-value = 0.0581

3. Average Savings:
   H0: |mean for scenario *0% core* - mean for scenario *100% core*| = 10
   H1: |mean for scenario *0% core* - mean for scenario *100% core*| $<$ 10
   Results: Z = -2.4495, p-value = 0.0072

4. Average Savings:
   H0: |mean for scenario *50% core* - mean for scenario *100% core*| = 10
   H1: |mean for scenario *50% core* - mean for scenario *100% core*| $<$ 10
   Results: Z = -3.444, p-value = 0.0003

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