

The Evolution of Industrial Clusters – Simulating Spatial Dynamics

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ABSTRACT. Industrial clusters have received much attention in economic research in the last decade. They are seen as one of the reasons for the economic success of certain regions in comparison to others. This paper studies the evolution of such industrial clusters. To this end, a spatial structure of regions is set up and the entry, exit, and growth of firms within these regions is modelled and studied with the help of simulations. We are able to obtain some knowledge about the basic characteristics of this dynamic process and about the spatial relation between industries that results. It is shown that it matters whether one or the other industry appears first and that location of clusters of one industry influence the location of other industries. Furthermore, some necessary conditions for the evolution of industrial clusters are identified.

KEYWORDS: evolution, industrial clusters, technological spillovers, simulations, spatial agglomeration.

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1. Introduction

Recently regional phenomenon have gained much attention within economics. Especially the question why certain regions are economically successful while others are not has been increasingly frequently discussed. The theoretical discussion of this phenomenon was triggered by various case studies of successful regions, like Silicon Valley, the Third Italy and many more (such case studies can, for example, be found in Rosegrant & Lampe 1992, Saxenian 1994, and Dalum 1995). On the basis of these case studies several authors have attempted to explain the specific reasons for the success of each of these regions. Furthermore, some general concepts have been developed and various mechanisms have been identified that are seen as the causes for the success of those regions. The four main concepts are those of industrial districts, industrial clusters, innovative milieux and regional innovative systems (descriptions can be found in Becattini 1990, Maillat & Lecoq 1992, Pyke & Sengenberger 1992, Scott 1992, Camagni 1995, van Dijk 1995, Markusen 1996, Lawson 1997, Rabelotti 1997; an attempt to structure these approaches can be found in Brenner 2000).

Although the literature on industrial districts and the likes has increased and is still increasing tremendously, most of the literature addresses the reasons for the success of such regional systems and does not deal in general with the question, how these spatial structures come into existence. In most of the case studies this question is addressed for the specific situation of the region that is studied. In the case of Third Italy historical aspects that led to an entrepreneurial spirit, a trustful atmosphere and helpful politics are suggested to be the determinants (cf. Dei Ottati 1994 and Rabelotti 1997). In the case of Route 128 research funds from the Department of Defence are seen as the initial driving force (cf. Rosegrant & Lampe 1992). While in the case of North Jutland a mixture of a wise creation of new institutes at the Aalborg university, the existence of a firm with experience in the relevant field and the change of the market are regarded to be the crucial factors for the evolution of this district (cf. Dalum 1995). Many other examples could be listed here – all with very specific explanations for specific developments.

The theoretical literature can be divided into two nearly separate strands. One is based on the above-cited case studies and tries to identify general mechanisms that make local systems successful without considering the question of how these mechanisms started. The other is based on the empirical finding that economic activity, on a general and an industrial level, is geographically concentrated (see for example the calculation of gini-coefficients in Krugman 1991a and the calculation of an index of geographic concentration in Ellison & Glaeser 1994). With respect to the latter, several theoretical approaches have been able to rebuild geographic concentration in simulations (cf. for example Camagni & Diappi 1991 and Jonard & Yildizoglu 1998). However, the aim of these studies was to obtain a final spatial distribution that is similar to the one observed in reality. The dynamics that lead to such a distribution are not discussed in this literature. Thus, a theoretical approach that deals on a general level with the questions of how, where and when industrial clusters evolve is missing. This paper makes a first step to fill this gap. The major aim is to model the dynamics that lead to the

evolution of industrial clusters. Through this, some first answers to the above questions are obtained.

The approach proposed here is based on simulating the spatial dynamics of two industries using first a number of unconnected regions. After the analysis of some basic aspects a cellular automaton is developed. This means that a two-dimensional space is divided into small quadratic units. This allows dealing with local interactions, both within a unit and between neighbouring units. Similar approaches are used in the literature on economic agglomeration (cf. Camagni & Diappi 1991, Krugman 1991b, Allen 1997a and 1997b, Schweitzer 1998, and Caniëls & Verspagen 1999) and industrial concentration (cf. Jonard & Yildizoglu 1998). However, the present approach deviates from these approaches in its aims and two structural aspects. The aim is to understand the evolution of industrially specialised regions in the context of a changing global environment. Instead of reproducing the distribution of economic agglomeration, this paper focuses on the change of the distribution of industrial activity and its path-dependency. To this end, two aspects are treated in more detail than it is done in the literature on agglomerations. First, the interaction between industries is explicitly modelled considering different courses of exogenous changes. Second, the processes within each geographical unit is modelled in detail, concerning the entry of firms, their growth and eventually their exit. The details of this are outlined in the next section.

The analysis by T. Brenner (2000) has shown that different mechanisms play a role during the evolution of an industrial cluster. Modelling all of them simultaneously would cause a simulation approach to be too complex to interpret the different results. Thus, it seems to be more adequate to restrict the modelling in each approach to a few self-augmenting processes, so that the impact of each mechanism can be understood in detail. Finally, the different mechanisms can be put together to get a comprehensive view of their complex interaction. This paper is restricted to two mechanisms. The first mechanisms are knowledge spillovers between firms of the same and of different industries and the local stickiness of these spillovers (for empirical aspects on this see Jaffe, Trajtenberg & Henderson 1992 and Audretsch 1998). The second mechanism is the founding of new enterprises. Both aspects have been identified to be major aspects of the evolution of industrial clusters (cf. Brenner 2000).

The paper proceeds as follows. In Section two the basic model is developed. Section three focuses on a case with five spatially independent regions. The dynamics found in simulations are analysed with respect to the concentration of industries within one or several regions and with respect to the spatial relation and spillovers between industries. In Section four the model is expanded to a situation with 49 regions that are located on a 7×7 grid and where spillovers between and spin-offs in neighbouring regions occur. The impact of these two aspects on the spatial distribution of two industries are studied and discussed. Section five concludes.

2. Basic model

The basic elements of the model are firms. Therefore, the presentation of the model starts with a discussion of the firm-specific variables and their dynamics.

Then, we turn to entry and exit of firms and the interactions between firms. Finally, the labour market and the global demand are discussed and modelled.

The state of each firm is characterised by several variables which all change endogenously. Furthermore, several parameters are defined that determine the behaviour of firms and their surrounding. These parameters are given exogenously and their influence on the spatial distribution of industrial activity is studied below.

The variables that define the state of a firm n ($\in \mathcal{N}(t)$) at time t ($t \in \{0, 1, 2, \dots\}$) are its capital $K_n(t)$ (measured in dollars), its labour force $L_n(t)$ ($\in \mathbb{N}$), its technology $T_n(t)$ ($\in \mathbb{R}_+$), and its liquidity $B_n(t)$ (measured in dollars). Furthermore, each firm is assigned to a region q_n ($\in \mathcal{Q}$) and an industry i_n ($\in \mathcal{I}$) which cannot be changed during the life of a firm.

The production function of a firm is assumed to depend on its attributes $K_n(t)$, $L_n(t)$, and $T_n(t)$. Besides these usual determinants, technological spillovers from other firms are assumed to influence the production capacity. Technological spillovers are frequently studied in the literature (cf. e.g. Grupp 1996). They include non-intended spillovers, like knowledge transfers by scientists and engineers switching between firms and improvements of the own products or production due to technological advances of suppliers, as well as intended spillovers, like those created by joint R&D-projects and strategic alliances. Especially, the first and the latter are important in a regional context.

These spillovers are the only kind of positive local external economies that are considered here. All other aspects of agglomeration economies that are discussed in the literature are excluded in this approach in order to restrict the model to a few local mechanisms. Thus, the model developed here is adequate only for analysing the evolution of an industrial cluster where firms profit from technological spillovers from other firms located in the same or neighbouring regions (cf. Brenner 2000). Industrial clusters that are based on vertical or horizontal contacts and co-operations are not adequately represented by this approach. Furthermore, this approach does not deal with the labour market in detail.

Spillovers are bound with respect to location and industry. Therefore, we define a value $S_{q,i}(t)$ ($\in \mathbb{R}_+$) which denotes the spillovers that a firm belonging to industry i at location q can profit from. The value of $S_{q,i}(t)$ is discussed below in detail. The spillovers and the technological state $T_n(t)$ of a firm determine the steepness of the production function. With respect to the production factors $K_n(t)$ and $L_n(t)$ a Cobb-Douglas production function is assumed here, so that the output $Y_n(t)$ (measured in units of the good, $Y_n(t) \in \mathbb{R}$) of firm n is given by

$$Y_n(t) = \Psi \cdot \left[T_n(t)^{\gamma_{i_n}} \cdot S_{q_n, i_n}(t) \right] \cdot K_n(t)^{\alpha_{i_n}} \cdot L_n(t)^{\beta_{i_n}} . \quad (2.1)$$

The partial output elasticities α_i and β_i are parameters that are identical for all firms of the same industry. They may, however, differ between industries. The same holds for γ_i . Ψ is a parameter with the unit $\frac{1}{\text{dollar}}$ which is set to $\Psi = \frac{1}{\text{dollar}}$ in the simulations.

It is assumed here that firms are not able to influence their technology $T_n(t)$ and the amount of spillovers $S_{q,i}(t)$. This means that the possibility to vary the amount of R&D-expenditures is neglected. All firms of one industry are assumed

to spend the same amount on R&D and, therefore, have the same probability to improve their technology. Whether a firm n is able to improve its technology at time t is a random event. With a probability $p_{I,i}$ a firm of industry i is assumed to innovate at time t , which improves its technology by 0.01. Thus, each improvement is an incremental step. The impact of this incremental step, however, is assumed to decrease with the value of the technology $T_n(t)$ that is already reached. Therefore, the value $T_n(t)^{\gamma_i}$ enters the production function with $0 < \gamma_i < 1$.

The amount of capital $K_n(t)$ and labour $L_n(t)$ that are used in the production process are chosen by the firm. To this end, the optimal factor inputs are calculated at each time for a given demand. The firms are assumed not to be able to predict the demand they face in the next period. Therefore, they take the average of the demands at the present and the previous time as an approximation for the demand they should expect in the next period, which is denoted by $\hat{D}_n(t)$ (the demand is measured in units of the good). Similarly, they assume wages, spillovers and their technology to remain constant. Given these assumptions, the firms are able to calculate the necessary factor inputs to satisfy the expected demand. However, they may vary the amount of labour and capital, provided that

$$\hat{D}_n(t) = \left[T_n(t-1)^{\gamma_{i_n}} \cdot S_{q_n, i_n}(t-1) \right] \cdot K_n(t)^{\alpha_{i_n}} \cdot L_n(t)^{\beta_{i_n}} \quad (2.2)$$

is satisfied. It is assumed that the firms try to optimise the proportion of the factor inputs $K_n(t)$ and $L_n(t)$. The proportion of factor inputs is optimal if the marginal productivity of all factor inputs are identical (cf. microeconomic textbook). This condition is satisfied if

$$r \cdot \alpha_{i_n} K_n(t) = w_{q_n}(t) \cdot \beta_{i_n} \cdot L_n(t) . \quad (2.3)$$

Inserting Equation (2.3) into Equation (2.2) leads to the following optimal capital and labour inputs:

$$K_{n,opt}(t) = \left(\frac{\hat{D}_n(t) \cdot w_{q_n}(t-1)^{\beta_{i_n}} \cdot \alpha_{i_n}^{\beta_{i_n}}}{\Psi \cdot \beta_{i_n}^{\beta_{i_n}} \cdot r^{\beta_{i_n}} \cdot T_n(t-1)^{\gamma_{i_n}} \cdot S_{q_n, i_n}(t-1)} \right)^{\frac{1}{\alpha_{i_n} + \beta_{i_n}}} \quad (2.4)$$

and

$$L_{n,opt}(t) = \left(\frac{\hat{D}_n(t) \cdot r^{\alpha_{i_n}} \cdot \beta_{i_n}^{\alpha_{i_n}}}{\Psi \cdot \alpha_{i_n}^{\alpha_{i_n}} \cdot w_{q_n}(t-1)^{\alpha_{i_n}} \cdot T_n(t-1)^{\gamma_{i_n}} \cdot S_{q_n, i_n}(t-1)} \right)^{\frac{1}{\alpha_{i_n} + \beta_{i_n}}} \quad (2.5)$$

where $w_{q_n}(t)$ (measured in dollars) denotes the wage rate in region q_n at time t and r is the interest rate on the capital market.

However, firms do not always change their capital and labour input to the optimal value within one period. The expansion of capital is costly and takes time, and capital investment is in general irreversible, while labour has to be hired and in some cases trained. Thus, it is assumed that capital increases by maximally 5% and decreases by maximally 10% each period. Furthermore, investment also depends on the liquidity $B_n(t)$ of a firm and is assumed to be determined in the following way. First, set $K_{n,\downarrow}(t) = 0.9 \cdot K_n(t-1)$ and $K_{n,\uparrow}(t) = 1.05 \cdot K_n(t-1)$.

Then,

$$K_n(t) - K_n(t-1) = \begin{cases} -0.1 \cdot K_n(t-1) & \text{if } K_{n,opt}(t) < K_{n,\downarrow}(t) \\ \frac{K_{n,opt}(t) - K_{n,\downarrow}(t)}{1 + \exp\left[\frac{B_n(t)}{K_{n,opt}(t) - K_{n,\downarrow}(t)}\right]} & \text{if } K_{n,\downarrow}(t) < K_{n,opt}(t) < K_{n,\uparrow}(t) \\ \frac{K_{n,\uparrow}(t) - K_{n,\downarrow}(t)}{1 + \exp\left[\frac{B_n(t)}{K_{n,\uparrow}(t) - K_{n,\downarrow}(t)}\right]} & \text{if } K_{n,opt}(t) > K_{n,\uparrow}(t) \end{cases} \quad (2.6)$$

This equation is arbitrarily chosen to reflect the fact that the higher the liquidity of a firm, the more money it will invest up to the level which is optimal and possible.

We assume that firms chose the amount of labour that they employ such that the marginal factor productivity is the same for capital and labour. Changes are restricted to a maximum of 50% of the previous labour input. However, since the labour input is related to the capital input, the dynamics of capital and labour inputs are in general limited by the restrictions on the changes of capital. $L_n(t)$ is always a natural number representing the number of employees.

The liquidity of firms is updated each period by subtracting the money invested ($K_n(t) - K_n(t-1)$), the costs of capital ($r \cdot K_n(t)$), the labour costs ($w_{q_n}(t) \cdot L_n(t)$), and the fixed costs F_{i_n} (measured in dollar) and adding the returns from selling the good on the market ($P_n(t) \cdot D_{n,s}(t)$). The fixed costs are an industry-specific parameter. $P_n(t)$ and $D_{n,s}(t)$ are described in detail below.

Firms are assumed to be price setters. As outlined above firms adapt their production to the demands they face. The price is set according to a mixture of markup-pricing and an orientation towards the market price. To use markup pricing, the costs of production have to be calculated. The average costs are

$$c_n(t) = \frac{F_{i_n} + r \cdot K_n(t) + w_{q_n}(t) \cdot L_n(t)}{Y_n(t)}. \quad (2.7)$$

The price $P_n(t)$ (measured in dollars) charged by firm n at time t is assumed to be given by

$$P_n(t) = \mu_{i_n} \cdot (1 + m_{i_n}) \cdot c_n(t) + (1 - \mu_{i_n}) \cdot \bar{P}(t-1) \quad (2.8)$$

where μ_i and m_i are industry-specific parameters and $\bar{P}(t)$ is the average price for which the good is traded on the market, which is called the market price in this approach. m_i is the mark-up used in industry i , while μ_i determines how much firms stick to the price resulting from the mark-up rule instead of orienting on the market price. The calculation of the market price is given in Equation (2.12).

Firms are removed either if they employ only one worker (this threshold is chosen for convenience) or if their liquidity falls below a certain trash-hold B_{min} .

New firms occur due to two processes: random entry and spin-offs. First, with a constant probability $p_{F,q}$ a firm enters at any time t for any industry (this probability may vary between regions). Such a firm starts with an initial set of variables given by K_{init} , L_{init} , and B_{init} . The initial value of T_n is determined by calculating the average value of $T_{\tilde{n}}(t)$ for all firms \tilde{n} that belong to the same industry. To this average value an amount of either 0, 0.01 or 0.02 is added with equal probability. This can be interpreted as follows. From time to time someone

has, starting from the average technological standard, an innovative idea and founds a new firm to exploit this idea.

Second, within a region with a probability, depending on the number of firms that belong to a certain industry and are located in this region, a spin-off firm is founded. The probability for such a spin-off is given by

$$\frac{N_{i,q} \cdot p_{S,q}}{N_{i,q} \cdot p_{S,q} - p_{S,q} + 1} \quad (2.9)$$

where $N_{i,q}$ denotes the number of firms in region q that belong to industry i and $p_{S,q}$ is a parameter, dependent on the region. A spin-off firm starts with the same initial variables as defined above, namely K_{init} , L_{init} , and B_{init} , except for the technology. To determine the technology of a spin-off firm, one of the firms of the same industry in the region is chosen randomly. The spin-off firm is assumed to be a spin-off of this firm and, therefore, imitates the technology of this firm. Again either 0, 0.01, or 0.02 is added with equal probability, representing the fact that the spin-off firm might innovate right at the beginning.

In empirical studies it has been repeatedly shown that firms profit a lot from spillovers from other firms. These spillovers have been shown to be to some extent a localised phenomenon (cf. Jaffe, Trajtenberg & Henderson 1992 and Audretsch 1998). Therefore, we consider local spillovers between firms in this approach. In a first approach, in Section 3 spillovers are assumed to occur only within regions. In Section 4 we will also allow for spillovers between neighbouring regions. Spillovers might occur within and between industries. The amount of spillovers within and between industries is denoted in the form of a spillover matrix $(s_{ij})_{i,j \in \mathcal{I}}$. The total spillover that a firm of industry i in region q profits from is defined by

$$S_{q,i} = \left[\sum_{\substack{n \in \mathcal{N}(t) \\ q_n = q}} s_{in} \cdot T_n(t) \right]^{\sigma_i}. \quad (2.10)$$

The influence of this spillover on the production function of each firm is given above in Equation (2.1).

Labour markets are assumed to be local in this approach. This means that we exclude any kind of movement of the labour force. Thus, a firm can only employ people from the region where it is located in. Wages result to be variables of the regions. A differentiation of the labour market with respect to industries is not considered. The wage rate $w_q(t)$ within a region is assumed to be given by

$$w_q(t) = w_{q,0} \cdot \left[\sum_{\substack{n \in \mathcal{N}(t) \\ q_n = q}} L_n(t) + L_{q,other} \right] \quad (2.11)$$

where $w_{q,0}$ is a parameter determining the basic wage level in region q and $L_{q,other}$ is a parameter denoting the labour demand of all other industries in region q that are not explicitly considered in the model. The labour demand of all other industries is assumed to remain constant. This parameter determines whether wages react more or less strongly to changes in the labour demand of the explicitly modelled firms.

All firms of one industry are assumed to produce the same kind of good.

Thus, they supply the same market and compete on this market. However, it is assumed that the goods are not identical, so that they are substitutable but not all customers will choose automatically the most inexpensive good.

Hence, to calculate the demand for each firm n , two steps are necessary. First, the overall demand has to be determined. Then, this demand has to be distributed between the firms of the respective industry. Demand is assumed to be global, so that no distinction with respect to the locality of firms is necessary. The overall demand for one kind of good is assumed to depend on the average price of the good, which was above called the market price. The average price for the good of industry i is given by

$$\bar{P}_i(t) = \sum_{\substack{n \in \mathcal{N}(t) \\ i_n = i}} [D_{n,s}(t-1) \cdot P_n(t)] \quad (2.12)$$

where for each firm the number of sold goods $D_{n,s}(t-1)$ in the last period is used to avoid a circular definition of demands. The market demand $\bar{D}_i(t)$ is assumed to be given by

$$\bar{D}_i(t) = \frac{\bar{D}_{i,0}}{\bar{P}_i(t)} \quad (2.13)$$

where $D_{i,0}$ is an industry-specific parameter.

The market demand $\bar{D}_i(t)$ is distributed between the firms of industry i according to their prices. The higher the price of a firm the smaller the demand for the good produced by this firm will be. However, since we assume that goods are not identical, firms with higher prices will still sell some pieces of the good, at least if their prices are not too high. To model these characteristics, a market share factor $M_n(t)$ is defined for each firm n by

$$M_n(t) = \begin{cases} \frac{\phi_{i_n} \cdot \bar{P}_{i_n}(t)}{P_n(t)} - 1 & \text{if } \frac{P_n(t)}{\bar{P}_{i_n}(t)} < \phi_{i_n} \\ 0 & \text{if } \frac{P_n(t)}{\bar{P}_{i_n}(t)} > \phi_{i_n} \end{cases} \quad (2.14)$$

where ϕ_{i_n} is an industry-specific parameter, which determines how much firms are able to charge for the good without being ignored by the customers. All firms with a price above $\phi_{i_n} \cdot \bar{P}_{i_n}(t)$ do not sell any piece of the good. Below this value the demand for a firm's good decreases with its price. The demand for the good of firm n is calculated according to

$$D_n(t) = \frac{M_n(t) \cdot \bar{D}_{i_n}(t)}{\sum_{\substack{\bar{n} \in \mathcal{N}(t) \\ i_{\bar{n}} = i_n}} M_{\bar{n}}(t)}. \quad (2.15)$$

This $D_n(t)$ equals the number of goods $D_{n,s}(t)$ that are sold by the firm if the firm is able to produce enough goods. If it is not able to do so, the number of goods sold equals the possible output, meaning $D_{n,s}(t) = Y(t)$.

3. Analysis of simulations with independent regions

Before we analyse a model with a spatial distribution of regions and spillovers between neighbouring regions, the above model will be simulated and analysed for five independent regions and two industries. For this setting the influence of

all parameter is studied in detail. This allows to restrict the analysis of the more complex spatial setting in the next section to the most important parameters.

The study of five independent regions proceeds in four steps. Firstly, the dynamics of the simulations are discussed. Secondly, a sensitivity analysis is conducted for all parameters. Thirdly, the parameters that cause firms to agglomerate in one or a few regions are analysed and discussed. Finally, the successive introduction of industries is studied.

3.1. DYNAMICS OF THE PROCESSES

The dynamics of simulations might take various forms. There might occur cycles, there might be some initial dynamics which come to rest after some time, or there might be chaotic dynamics. In the simulations conducted here we observe some initial dynamics that come to a rest after at least 2000 periods, except of some small fluctuations. This holds independent of the set of parameters. In most cases the stationary state is reached before the first 500 periods are finished. Only a few simulation runs have offered some surprising change in the spatial structure in a later period (see for example Figure 1). Thus, after an initial phase the spatial distribution of economic activity remains constant, independent of the choice of the parameters, if the exogenous circumstances do not change.

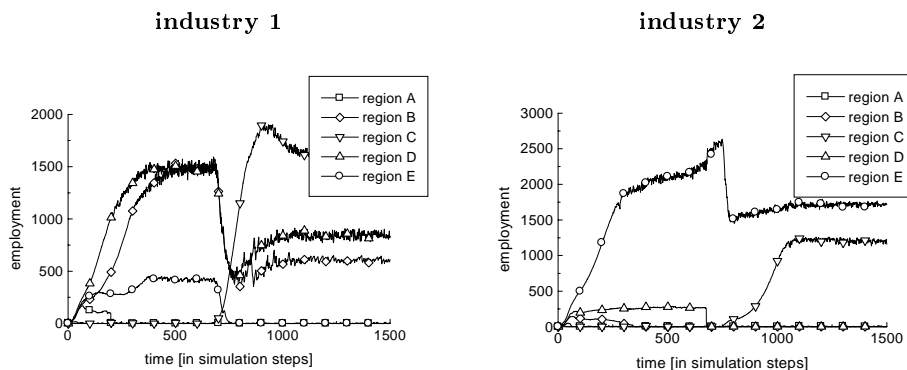


Figure 1: Exemplary dynamics for the standard parameter set, except $F_i = 0 \forall i = 1, 2$.

Re-running a simulation with the same parameters often leads to a different stationary spatial distribution of firms and employment. The processes simulated show a clear path-dependence with respect to two aspect. First, if there is a concentration of economic activity in some regions, the regions that contain this concentration vary from simulation run to simulation run. Such a characteristic is also found in other simulations of spatial processes (cf. Krugman 1991b, Allen 1997a and 1997b, and Schweitzer 1998).

Second, for many parameter sets the spatial structure of the stationary spatial distribution of firms and employment also varies – a characteristic that is not

reported in other studies. There are, for example, parameter sets where in one run the firms concentrate in one region while in the next run they are distributed over four of the five regions. Similarly, there are parameter sets where in one run the firms of both industries agglomerate in the same region while in the next run the firms of one industry are distributed over three regions and the firms of the other industry agglomerate in another region. For many of the parameter sets there seems to be no stable spatial distribution of firms and employment to which every simulation converges. Thus, path-dependency does not only occur with respect to the regions where firms agglomerate, but also with respect to the number of regions that contain an agglomeration and the spatial relation between industries.

3.2. SENSITIVITY ANALYSIS FOR ALL PARAMETERS

The following analysis is restricted to the state that is reached in the simulations after 3000 periods. Since, we have never observed any significant changes after the first 2000 periods, the state after 3000 periods is used as an approximation of the final state. This state is characterised according to four aspects: 1) the number of regions that contain a significant number of employment of an industry, denoted by Q_s , 2) the share of those regions that contain also a significant number of employment of the other industry, denoted by Q_d , 3) the total number of employment, denoted by L and 4) the total number of firms, denoted by N .

The aim of the sensitivity analysis is to identify for each parameter those aspects that are influenced by the parameter. Therefore, each parameter is varied in both directions and a statistical analysis of the resulting changes in Q_s , Q_d , L , and N is conducted. Before this can be done, a standard parameter set has to be defined. We have chosen this parameter set such that it leads to some intermediate results according to the aspects above, meaning that there is neither a complete concentration in one region nor an equal distribution of the employment over all region and that there is neither a strict separation of the two industries nor a strict coexistence. This standard parameter set is given by $\alpha_i = 0.5$, $\beta_i = 0.5$, $\gamma_i = 0.4$, $\sigma_i = 0.4$, $p_{I,i} = 0.1$, $F_i = 1$, $r = 0.1$, $m_i = 0.05$, $\mu_i = 0.7$, $B_{min} = -10$, $p_{F,q} = 0.1$, $p_{S,q} = 0.02$, $K_{init} = 5$, $L_{init} = 5$, $B_{init} = 10$, $s_{ii} = \frac{1}{3}$, $s_{ij} = \frac{1}{9} \forall i \neq j$, $w_{q,0} = 0.0001$, $L_{q,other} = 1000$, $\bar{D}_{i,0} = 2000$, and $\phi_i = 1.5$. Furthermore, the simulations are started in the standard case with no firms existing and an initial value of technology of $T_{init} = 1$. The spillovers for each region and industry are set to $S_{q,i} = 0.5$ if no corresponding firm exists. The results of the sensitivity analysis are given in Table 1.

Table 1 shows that only a few parameters have no influence on the final state of the simulations. Most of the parameters influence all four aspects. Below the focus of the analysis will be on those parameters that influence the industrial, geographical concentration and the spatial relation between the two industries, since the aim of this approach is to understand the spatial distribution of economic activity.

	Q_d	Q_s	L	N
$\alpha_i (K_{init} = 10 \cdot \alpha_i)$	0	-	-	-
$\beta_i (K_{init} = \frac{2.5}{\beta_i})$	-	U	+	-
γ_i	0	0	0	0
σ_i	U	-	-	-
$p_{I,i}$	+	0	-	0
F_i	-	U	0	-
$r (K_{init} = \frac{1}{2r})$	0	-	-	+
m_i	0	+	+	+
μ_i	+	+	+	-
B_{min}	0	0	0	0
$p_{F,q}$	+	+	0	+
$p_{S,q}$	0	+	0	+
B_{init}	0	U	+	+
s_{ii}	-	-	+	-
s_{ij}	+	+	-	0
$L_{q,other} (w_{q,0} = \frac{0.1}{L_{q,other}})$	+	-	+	0
$\bar{D}_{i,0}$	-	+	+	+
ϕ_i	0	+	0	+

Table 1: Results of the sensitivity analysis. To obtain these results, for any parameter two values well above and below the standard value have been used and the differences of the resulting values Q_d , Q_s , L , and N studied. '+' denotes a positive influence, '-' a negative influence, 'U' denotes an influence that leads to an increase for low and for high values of the parameter, and '0' denotes no significant influence (the results are all significant at 0.001).

3.3. GEOGRAPHIC INDUSTRIAL CONCENTRATION

The aim of this approach is to develop a better understanding for the evolution of industrial clusters. Therefore, the parameters that influence the degree of concentration deserve a comprehensive treatment. Above it has been reported that quite a few parameters have an impact on the number of regions that are populated with a significant number of firms in the long run. These are α_i , β_i , σ_i , F_i , r , m_i , μ_i , $p_{F,q}$, $p_{S,q}$, B_{init} , s_{ii} , s_{ij} , $L_{q,other}$, $\bar{D}_{i,0}$ and ϕ_i .

However, the influence of these parameters on the geographic industrial concentration is of different strength. To find those parameters that are most relevant, we use an experimental design and analyse the results statistically (cf. Witt 1986 where a similar approach is taken on a related topic and Winer 1971 where the method is discussed generally). The dependent variable that is to be explained is the number of regions with a significant number of employment of an industry D_s . The independent variables are all parameters that have been identified to have an influence on D_s . For each independent variable we choose two or three (in the case of a U-shaped dependence) values such that the corresponding values of D_s differ from each other by the same amount (approximately 0.5) for all parameters. In the case of s_{ii} and s_{ij} such a difference cannot be obtained. A difference of around 0.3 was obtained for these parameters. The values for all parameters that are included are given in Table 2.

A simulation is run for each combination of these values, meaning that in total 110592 simulations are run. For each run D_s is recorded. It is assumed that D_s can be explained as a linear combination of the values of α_i , β_i , σ_i , F_i , r , m_i , μ_i , $p_{F,q}$, $p_{S,q}$, B_{init} , s_{ii} , s_{ij} , $L_{q,other}$, $\bar{D}_{i,0}$, and ϕ_i . Therefore, a multiple regression is conducted with the results given in Table 2. The regression factors show the amount of changes in D_s that each of the parameters causes[†]. This first of all reveals that four parameters, namely F_i , r , B_{init} and $\bar{D}_{i,0}$ have no consistent significant influence on D_s if all parameters are varied.

To gather more information about the relevance of the remaining parameters the regression is conducted for each parameter separately. One may claim that a parameter dominates another parameter if the changes of the depended variable are mainly explained by the former, although both parameters are changed such that according to the sensitivity analysis both should lead to the same variation of the dependent variable. Therefore, we use the R^2 -value of the separate regression as a measure of the explanatory power of each parameter. This value is given in the last row of Table 2.

The parameter with the highest R^2 is the number of employees $L_{q,other}$ in other industries within a region. This can be interpreted as follows. If wages react strongly on the change in the demand for labour, firms tend to distribute equally between regions. If, instead, wages are quite inelastic with respect to changes in the demand for labour, the tendency towards spatial concentration is supported. The reaction of wages depends on the relation between the number of employees within an industry and the total labour force available. Industries with a high total employment have a much stronger effect on local wages if they agglomerate in a region than industries with a low total employment. Thus, industries with many employees should be expected to concentrate less.

The parameters $p_{F,q}$ and $p_{S,q}$ have also a strong impact on D_s . They determine the frequency with which start-ups occur. Their impact can be explained as follows. At the beginning of the simulations start-ups are very likely to survive due to the missing competition from other firms. Once a number of large firms have established, start-up firms usually exit after a short period of time. Therefore, the final distribution is strongly influenced by the events at the beginning.

[†] Of course, this approach does only result in some local and linear knowledge about the dependence of D_s on the parameters.

	low value	middle value	high value	regression factor	significance level	R^2 for separate regression
α_i	0.45		0.55	-2.600	0.0001	0.0079
β_i	0.47	0.49	0.54	1.2855	0.01	0.0005
σ_i	0.36		0.44	-4.322	0.0001	0.0139
F_i	0.83	0.9	1.75	0.0266	0.1	0.0001
r	0.097		0.103	-0.1886	-	0
m_i	0.035		0.065	11.8885	0.001	0.0148
μ_i	0.6		0.8	-0.2207	0.1	0.0002
$p_{F,q}$	0.05		0.3	3.1534	0.0001	0.0724
$p_{S,q}$	0.005		0.7	0.9928	0.0001	0.0555
B_{init}	2	8	25	0.0035	0.1	0.0003
s_{ii}	$\frac{1}{18}$		1	-0.5902	0.0001	0.0362
s_{ij}	$\frac{1}{36}$		$\frac{1}{3}$	1.1990	0.0001	0.0156
$L_{q,other}$	400		3000	-0.0006	0.0001	0.2819
$\bar{D}_{i,0}$	200		8000	0.000002	-	0
ϕ_i	1.3		2	0.5823	0.0001	0.0194

Table 2: Results of the multiple and the separate regressions.

A higher frequency of entries in all regions leads to a more equal distribution between regions. This distribution manifests itself with time. Thus, industries with a high frequency of entries at the beginning should be expected to be less concentrated.

Furthermore, s_{ii} has a stronger impact on D_s than most of the other parameters. s_{ii} determines the amount of spillovers within an industry. Spillovers are repeatedly supposed to be one of the most important reasons for economic agglomerations in the literature, a view that is supported by this study. The more spillovers occur, the more economic activity will concentrate. Thus, industries where firms profit very much from spillovers should be spatially more concentrated than industries where firms profit less from spillovers.

3.4. SPATIAL RELATION BETWEEN INDUSTRIES

To obtain a better understanding for the spatial relation between industries, an approach similar to the one above is taken. The parameters that have been

found to influence Q_d in the sensitivity analysis are β_i , σ_i , $p_{I,i}$, F_i , μ_i , $p_{F,q}$, s_{ii} , s_{ij} , $L_{q,other}$ and $\bar{D}_{i,0}$. Again, for each of these parameters two or three values have been chosen such that Q_d varies by an amount of approximately 0.3, except of F_i and $\bar{D}_{i,0}$ where the variations of Q_d are 0.15 and 0.25, respectively. For each parameter combination a simulation has been run, implying a total number of 1536 simulation runs. A regression analysis has been conducted with the results given in Table 3.

	low value	middle value	high value	regression factor	significance level	R^2 for separate regression
β_i	0.44		0.56	-0.2718	0.0001	0.0060
σ_i	0.2	0.4	0.9	0.0584	0.0001	0.0043
$p_{I,i}$	0.01		0.4	0.0023	-	0
F_i	0.7		1.7	0.0054	0.1	0.0002
μ_i	0.5		0.86	0.2928	0.0001	0.0622
$p_{F,q}$	0.05		0.3	0.28	0.0001	0.0274
s_{ii}	$\frac{1}{9}$		$\frac{2}{5}$	-0.8139	0.0001	0.3096
s_{ij}	$\frac{1}{12}$		$\frac{1}{8}$	1.4508	0.0001	0.0205
$L_{q,other}$	100		3000	-0.000005	0.001	0.0011
$\bar{D}_{i,0}$	200		20000	-0.0000002	0.1	0.0001

Table 3: Results of the multiple and the separate regressions.

Table 3 shows a clear domination of four parameters, namely s_{ii} , μ_i , $p_{F,q}$ and s_{ij} .

The domination of s_{ii} can be explained as follows. An high value of s_{ii} causes the firms of an industry to be distributed over a large number of regions. Since the number of regions has been restricted to five, this means that the two industries are not able to locate in different regions. This aspect seems to be less relevant in reality where much more than five locations exist.

A high value of $p_{F,q}$, as discussed above, leads to a low concentration of industries and therefore more local coincidences between the industries, again due to the limitation of the total number of firms to five. The parameter μ_i has a similar impact. A large value of μ_i causes start-ups, which generally produce less efficient than existing firms due the economies of scale, to charge prices much higher than the market price. As a consequence, less start-ups survive and the concentration of industries decreases. Hence, according to the argument above, the probability of both industries to be located in the same region increases. Again both mechanisms require a restricted number of regions to work properly.

Thus, s_{ij} is the only parameter that can be expected to matter also in reality. It denotes the amount of spillovers between the industries.

3.5. DYNAMICS FOR THE SUCCESSIVE INTRODUCTION OF INDUSTRIES

Above it has been found that the spatial distribution of industries shows a strong path-dependency. This implies that one should expect the resulting spatial distribution to depend strongly on the temporal order of exogenous events. To test this implication, we study the successive introduction of the two industries. The first industry is introduced right at the beginning of the simulations and the second one is added after 1500 simulation steps, after the spatial distribution for the first industry has converged. Five parameter sets are studied. All parameter sets correspond with the standard parameter set except of the values of $L_{q,other}$ and s_{ij} . The values of these parameters are given by 1) $L_{q,other} = 10000$ and $s_{ij} = \frac{1}{9}$, 2) $L_{q,other} = 100$ and $s_{12} = s_{21} = \frac{1}{3}$, 3) $L_{q,other} = 10000$ and $s_{12} = s_{21} = \frac{1}{100}$, 4) $L_{q,other} = 100$ and $s_{ij} = \frac{1}{9}$, and 5) $L_{q,other} = 1000$ and $s_{12} = s_{21} = \frac{2}{9}$. For the parameter sets 1) and 3) the successive introduction of the industries does not change the results.

For the parameter set 5) the final distribution looks identical to those of the simulations where both industries have been introduced at the same time. However, the introduction of the second industry affects the spatial distribution of the first industry. If the second industry locates in a region that contains already an agglomeration of the first industry it reduces the labour demand of the first industry's firms due to rising wages in the region. Thus, the location of a new industry in a region might have a negative impact on the industry that is already located there. However, the opposite result might also occur. The location of the new industry in a so far 'empty' (industries that are not considered in the model might, of course, be located there) region might trigger the founding of firms belonging to the first industry. This might even lead to a situation where this region becomes dominant in both industries as can be seen in Figure 2.

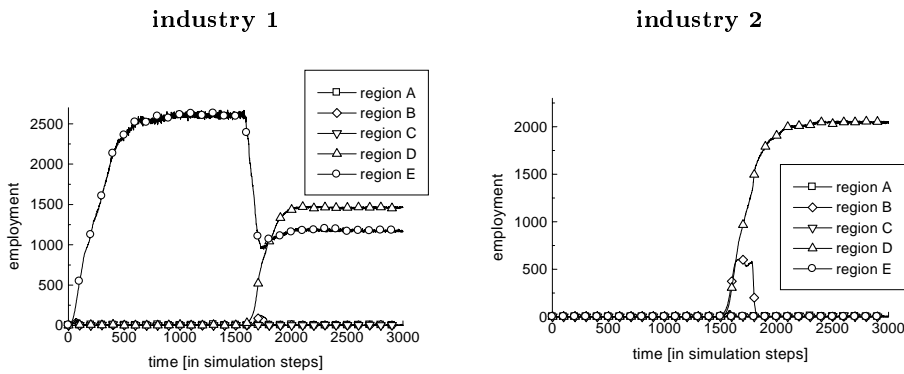


Figure 2: Exemplary dynamics for a successive introduction of the two industries with the standard parameter set, except $s_{12} = s_{21} = \frac{2}{9}$.

In the cases 2) and 4) we observe significant differences in the stationary spatial distribution of industries if we compare the distribution for a situation where the industries are introduced successively with the one for a situation where they are introduced simultaneously. While only one industry is present, the firms of this industry become distributed over between three and five regions. Subsequently, the second industry is only able to get hold in one or two regions, whereby it sometimes displaces the first industry. As a consequence, the second industry is present in a smaller number of regions than the first one and is therefore more concentrated, although both industries are characterised by exactly the same parameters. This means that the concentration of an industry also depends on the time at which it is introduced. However, whether the second industry concentrates more or less depends very much on the share of regions that are already occupied by the other industry. In reality, if industries concentrate spatially, each industry is in general agglomerated in only a few regions so that there should be plenty of regions left for new industries.

The stationary spatial distributions that are found in the cases 2) and 4) are similar. In the studies with a simultaneous introduction of both industries, however, the respective distributions are found to be significantly different. In case 2) the firms of the two industries have concentrated in the same region, while in case 4) firms of different industries have been located in different regions. The first feature disappears if the industries are introduced successively. For a successive introduction of industries the firms of the second industry either locate in the region that is not populated by the first industry or supersedes the firms of the first industry. Thus, the successive introduction of industries seems to make a spatial coincidence of industries less likely.

4. Analysis of a spatial model

In the last section the regional agglomeration of industries has been intensively studied given that technological spillovers are only taking place within regions. The spatial dimension of technological spillovers (cf. Jaffe, Trajtenberg & Henderson 1992) has been neglected. The impact of this aspect on the location of industries is studied in this section. All other aspects of the spatial distribution of industries, like its path-dependency, the determinants of industrial concentration and the dynamics of the related processes, which have been discussed in the last section, are neglected here.

4.1. SPATIAL MODEL

There are two kinds of technological spillovers between neighbouring regions that are considered in this approach: spillovers that influence the production function of firms in the neighbouring regions and spin-offs that are founded in neighbouring regions.

To be able to include these two aspects in the above model, a spatial structure has to be defined. We use a two-dimensional space with 49 quadratic regions of the same size. The space is assumed to have the form of a torus, so that the regions at the top of the space are neighbours to the regions at the bottom and the regions at the right of the space are neighbours to those on the left. Regions

are called neighbours if they share a one-dimensional border. Hence, each region has four neighbours.

In the above model a spillover value $S_{q,i}(t)$ has been defined for each region and industry (see Equation (2.10)). Now, spillovers from neighbouring regions are added. Thus, the spillover $\tilde{S}_{q,i}(t)$ is redefined according to

$$S_{q,i} = \left[\sum_{\substack{n \in \mathcal{N}(t) \\ qn=q}} [s_{iin} \cdot T_n(t)] + \sum_{\substack{n \in \mathcal{N}(t) \\ i_{\tilde{n}}=i \\ qn=q \leftarrow, q \rightarrow, q \uparrow, q \downarrow}} [\eta_q \cdot s_{ii} \cdot T_n(t)] \right]^{\sigma_i}. \quad (4.1)$$

where η_q denotes the region-dependent share of technology that spills over to neighbouring regions and $q \leftarrow, q \rightarrow, q \uparrow$, and $q \downarrow$ denote the four regions that are neighbours to region q .

The model above considers two kinds of entries: a random entry and a spin-off process that is restricted to spin-offs within the region. In this section a third process is added: a spin-off process where the spin-off firm is founded in one of the neighbouring regions. The probability for such a spin-off is given as one fourth of

$$\frac{N_{i,q} \cdot p_{N,q}}{N_{i,q} \cdot p_{N,q} - p_{N,q} + 1} \quad (4.2)$$

for each of the neighbouring regions, where $p_{N,q}$ is a region-specific parameter.

4.2. ANALYSIS OF INDUSTRIAL CONCENTRATION

Four parameters are studied in detail in the following analysis: the elasticity of wages, determined by $L_{q,other}$, the amount of spillovers between industries s_{ij} , and the two new parameters $s_{n,i}$ and $p_{N,i}$. The analysis aims to identify their impact on the concentration of industries and the spatial relation between industries.

To measure the concentration of industries and the spatial relation between industries, a specific distance measure is defined. First, we define the distance between two regions q and \tilde{q} on the basis of neighbourhood relations. Let \mathcal{S} be the shortest sequence of steps that connects the two regions with each other, where a step is a connection between two neighbouring regions. The distance $d(q, \tilde{q})$ is given as the number of steps in this sequence. The distance between two firms n and \tilde{n} is given by $d(n, \tilde{n}) = d(q_n, q_{\tilde{n}})$. The average distance between employees of industry i is then given by

$$d_i(t) = \frac{\sum_{\substack{n \in \mathcal{N}(t) \\ i_n=i}} \sum_{\substack{\tilde{n} \in \mathcal{N}(t) \\ i_{\tilde{n}}=i}} [L_n(t) \cdot L_{\tilde{n}}(t) \cdot d(n, \tilde{n})]}{\sum_{\substack{n \in \mathcal{N}(t) \\ i_n=i}} \sum_{\substack{\tilde{n} \in \mathcal{N}(t) \\ i_{\tilde{n}}=i}} [L_n(t) \cdot L_{\tilde{n}}(t)]} \quad (4.3)$$

while the average distance between the employees of different industries is given by

$$d_{ii}(t) = \frac{\sum_{\substack{n \in \mathcal{N}(t) \\ i_n=i}} \sum_{\substack{\tilde{n} \in \mathcal{N}(t) \\ i_{\tilde{n}}=\tilde{i}}} [L_n(t) \cdot L_{\tilde{n}}(t) \cdot d(n, \tilde{n})]}{\sum_{\substack{n \in \mathcal{N}(t) \\ i_n=i}} \sum_{\substack{\tilde{n} \in \mathcal{N}(t) \\ i_{\tilde{n}}=\tilde{i}}} [L_n(t) \cdot L_{\tilde{n}}(t)]}. \quad (4.4)$$

In the case of two industries we obtain three distances, d_1 , d_2 and d_{12} , as dependent variables.

To study the relation between the dependent and independent variables, we again conduct simulation experiments. For each of the independent variables three values are chosen: $s_{n,i} = \frac{1}{24}, \frac{1}{9}, \frac{1}{3}$, $p_{N,i} = 0.01, 0.02, 0.08$, $L_{q,other} = 100, 1000, 10000$, and $s_{ij} = \frac{1}{9}, \frac{2}{9}, \frac{1}{3}$. For each combination of these parameters (all other parameters are set to their standard value) one simulation is run and the distance measures are calculated after 2000 steps. A multiple regression is then conducted for each distance measure with all parameters, their logarithms, and their products of second order as independent variables. All significant independent variables and the respective results of the regression are listed in Table 4.

	d_1	d_2	d_{12}
$L_{q,other}$			0,13135*
$\ln(\eta_q)$	-0,1947*		
$\ln(s_{ij})$	0,24406*	0,29153*	-0,57965*
$\ln(L_{q,other})$	-0,41564***	-0,36228***	-0,37086**
$p_{N,q} \cdot \eta_q$		-15,61138*	42,98076***
$p_{N,q} \cdot L_{q,other}$	1,08222**	1,10365***	
$\eta_q \cdot L_{q,other}$	0,18518*		
$L_{q,other} \cdot s_{ij}$		-0,49465*	
adjusted R^2	0.51274	0.54989	0.49773

Table 4: Regression factors for all significant independent variables (* = significant at 0.1, ** = significant at 0.01, *** = significant at 0.001).

Three aspects of these results are worth a detailed discussion. First, all three dependent measures are not well explained by the regression results (R^2 is approximately one half). This is mainly due to the high fluctuations of the results for each parameter set which are caused by the strong dependence on single random events (cf. the discussion of path-dependency above).

Second, the industrial concentration depends only on the value of $L_{q,other}$ and a combination of this value and the likelihood of spin-offs in neighbouring regions. Spillovers to neighbouring regions that lead to a higher productivity, do not play a significant role for the degree of industrial concentration. The value of $L_{q,other}$ influences the industrial concentration in a logarithmic way in the direction that was also found above.

Third, the distance between the two industries decreases also with the logarithm of $L_{q,other}$. Furthermore, the distance between the two industries depends on the two new processes, determined by the parameters η_q and $p_{N,q}$. The dis-

tance between the two industries increases with the product of these parameters. This can be understood as follows. If one region contains a high number of firms of one industry, the neighbouring regions are likely to be populated by the same industry if η_q and $p_{N,q}$ are large. As a consequence, the other industry is less likely to locate in a neighbouring region and the distance between the industries increases.

5. Conclusion

This paper presents a first step towards the study of the evolution of industrial clusters. In the literature several mechanisms are identified which are claimed to be involved when industrial clusters evolve. For some of these mechanisms the existence has been proved empirically. However, this does not necessarily imply that they are responsible for the evolution of industrial clusters. Other mechanisms are only postulated.

One of the mechanisms, namely technological spillovers, is studied with the help of simulations here. It has been shown empirically that technological spillovers exist. Furthermore, it is frequently claimed that they influence the location of firms and thus also the formation of industrial clusters. Given the fact that technological spillovers exist, this approach studies how such spillovers, in the form of direct spillovers and spin-offs, influence the spatial distribution of firms.

One aim has been to test whether technological spillover might be the reason for the evolution of industrial clusters. It has been shown that such a causation might indeed take place. Furthermore, several further details of this causation have been studied. Especially the resulting spatial distribution of industries and their relation are of interests. It has been found that the spatial structure converges to a stationary distribution, independent of the parameters chosen. However, this stationary distribution seems not to be a stable one. Instead, the dynamics show a strong path-dependence, which includes in many cases also the structure of the spatial distribution. Furthermore, it has been found that the spatial relation between industries, in form of the average distance between firms, depends significantly on the wage elasticity and spillovers between neighbouring regions. The amount of spillovers between industries has an impact on this relation which is only slightly significant. With respect to the question of whether industries are located in the same or different regions, technological spillovers seem to matter.

All these findings can be empirically tested. The approach of this paper leads to a number of predictions that should be satisfied in reality if technological spillovers have a dominating influence on the location of industries. Therefore, the next step of the research agenda is to test those predictions. This can be done for all industries separately and would lead to some knowledge about the influence of technological spillovers for each industry. Subsequently, one might even check the other parameters that are found in this paper to influence the spatial distribution of firms. Most of these parameters, namely the frequency of start-ups, the amount of technological spillovers and the mark-ups, are industry-specific and should allow to make some prediction about the industries that are more or less concentrated.

In addition, this approach has been restricted to a few local mechanisms. More

similar approaches are necessary to obtain a complete picture of the processes that are involved in the evolution of industrial clusters. Especially, the process of innovation, the influence of public research institutions, infrastructure, and politics, and the labour market are planned to be modelled in more detail. Then, the results of these simulations should also be tested and compared with empirical data. Some of this is planned to be done in further projects, some of it might be taken up by other researchers.

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