Testing a model of exploration and exploitation as innovation strategies

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Abstract We suggest a structural model that specifies firm growth as a function of firm-specific parameters, market-specific parameters, and competition for purchasing power. The model distinguishes between two firm innovation strategies: exploration and exploitation. On the basis of a set of simulations of this model, we derive a number of empirically testable hypotheses. A subset of these have already found support in the empirical literature. We take these as evidence in favor of the explanatory power of the model. In addition, we are able to derive further testable propositions on the interaction of firm-demographic processes, innovative behavior and market structure that go beyond the existing literature and that we suggest for further research. We conclude that the approach chosen here provides a fruitful pathway for further research.

Keywords Firm size distribution · Innovation strategies · Industrial dynamics · Firm demography · Carrying capacity · Market concentration · Rank order turbulence

JEL Classifications L60 · O30 · G30 · L26

1 Introduction

Firm heterogeneity is largely accepted as an empirical fact in industrial economics. Firms differ in their growth rates and patterns and there is therefore a persistent firm size distribution within industries (Ijiri and Simon 1977; Mata and Portugal 1994; Caves 1998; Geroski 1998). In this article, we suggest a model that allows to study the relation between firm heterogeneity in terms of size and innovation strategy on the one hand and the dynamics of firm size distribution and the resulting market structure on the other. In the literature, this relation is approached by two different lines of argument.

One strand of literature claims that firm heterogeneity reflects a given unequal distribution of capabilities among entering firms and the experimentation process by which they discover this distribution. In this spirit, Lucas (1978) assumes that entrepreneurial abilities are randomly distributed in the population and that entrepreneurs progressively adapt their scale of production to their revealed level of capability. Jovanovic (1982) assumes that new firms draw a productivity parameter from a distribution unknown to them and also progressively discover their efficiency and adapt their size to the optimal size corresponding to the parameter they have drawn. In those models, the

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firm size distribution that prevails in equilibrium is a limit distribution of some underlying distribution: the distribution of managerial capabilities within society in the case of Lucas, and the distribution of cost efficiency across firms in the case of Jovanovic. Ericsson and Pakes (1995) adapt Jovanovic's model to the case where firms are able to modify their productivity over time through investments. In their model, firm size distribution is independent of the initial distribution of productivity; it reflects different abilities to perform in the market resulting from firms' attributes, both initial and learned.

A second strand of literature claims that firm heterogeneity results from systematic biases in the way different types of firms are able to realize and then capture available economic opportunities. In this line of argument, a given industry is characterized by a 'technological regime' which favors the introduction of innovation by either new or established firms, and which thus introduces systematic biases in the growth patterns of firms. Depending on which regime applies, market structure is found to be more or less concentrated and turbulent (Nelson and Winter 1982; Audretsch 1991, 1995; Baldwin 1995; Malerba and Orsenigo 1995, 1996; Agarwal and Gort 1996; Davies et al. 1996; Acs and Storey 2004).

The motivation for the model to be developed in this article is to draw on the phenomena emphasized by these two strands of literature, which we believe should be fruitfully explored in conjunction. While the literature on technological regimes provides important insights into the systematic biases that affect firm heterogeneity, it overlooks the microprocesses of innovation, learning and growth through which that heterogeneity takes place. On the other side, so-called learning models (e.g., Fudenberg and Levine 1998) offer a microeconomic foundation for firm heterogeneity that interestingly emphasizes the dynamic experimental processes inherent to firm entry and growth, but assumes away the systematic biases that may arise in firm growth patterns. Our objective is therefore to develop a model that (a) founds firm heterogeneity in dynamic microprocesses of experimentation and learning but that (b) allows the outcomes of those processes to be affected by systematic biases.

In order to achieve this objective, we propose to model firm growth patterns as resulting from a dynamic process of different innovation strategies,

namely the 'exploration' and 'exploitation' (March 1991) of existing economic opportunities (or, to put it differently, the space of existing technological knowledge). Firms that have successfully explored these opportunities, hence firms who offer a successful product, can start to exploit their product. In our model, the probability of shifting to exploitation depends on a set of environmental variables such as the cost of exploration, the market size or the growth rate of the market. This approach allows us to investigate the relation between these two types of innovation strategies, their consequences on firm survival and growth and the consequences on market structure.

Our model aims to investigate a large number of firms which are heterogeneous in terms of their size, their R&D-intensity and their cost structure. In order to capture this heterogeneity, we implement a simulation approach where we can vary these firm level parameters as well as the environmental variables. From these simulations, we derive a number of testable hypotheses. To our knowledge, this approach, involving (1) specification of a structural model (2) simulation and (3) deduction of propositions, has not been used previously. The propositions suggested here are no more than a subset of their possible number: the richness of results has not been tapped completely. In our view, this approach represents a fruitful avenue for further research.

The following section provides a comprehensive review of the literature that we draw upon to develop the model. Section 3 describes the model. Section 4 describes the simulation approach. Section 5 presents the results and discusses them. Section 6 concludes.

2 Exploration versus exploitation

In the definition of March (1991), "the essence of *exploitation* is the refinement and extension of existing competencies, technologies, and paradigms (...) The essence of *exploration* is experimentation with new alternatives." For March (1991, 1996) exploration and exploitation are fundamentally incompatible. As Gupta et al. (2006, pp. 694–695) put it, March's argument goes as follows:

both types of actions are iteratively self reinforcing. Because of the broad dispersion in the range of

possible outcomes, exploration often leads to failure, which in turn promotes the search for even newer ideas and thus more exploration, thereby creating a ‘failure trap.’ In contrast, exploitation often leads to early success, which in turn reinforces further exploitation along the same trajectory, thereby creating a ‘success trap.’ In short exploration often leads to more exploration and exploitation to more exploitation.

Hence, we have firms that persistently fail to find a good idea and firms that succeed early in finding a good idea and that subsequently survive on exploiting that idea. Interestingly enough, based on their empirical study of innovation and firm growth, Geroski et al. (1997) make the claim that “there is a threshold beyond which some form of ‘dynamic economies of scale’ operate and lead to a pattern of persistent innovation [and thus survival and growth], but this threshold is far too high for most firms to qualify. Most firms just do not innovate persistently.” This view suggests the following five arguments on the relation between innovation strategies and firm size.

First, firm success is the ability to innovate persistently or to ‘exploit’ a good idea, because it is precisely this persistence that allows to create a ‘success trap,’ hence to survive and/or grow. This is consistent with empirical findings about the relationship between growth and the level of persistence in firm innovation. Baldwin and Johnson (1999) give evidence that stronger innovative activity increases firms’ growth potential. In their sample of firm start-ups, they find that faster-growing entrants are more innovative than slower-growing ones. Baldwin et al. (1994) confirm this finding by showing that innovation is the key factor that differentiates between more or less successful firms. Moreover, Geroski et al. (1997) find that innovators tend to be persistent, exhibiting serial correlation of growth rates.

Second, the fact that a firm is successful may reveal itself only after the firm has grown enough to position itself on a ‘trajectory’ that can be exploited. This is consistent with the fact that firms ‘in experimentation’ are small, while firms exploiting a trajectory are larger. Likewise, Stuart and Podolny (1996) find that large firms tend to innovate along standard and well explored fields. Almeida and Kogut (1997) and Almeida (1999) find that small firms are more likely to explore technologically diverse and uncrowded

territories, leaving the domination of more mature technologies to larger firms. Baldwin and Johnson (1999) find that small firms are superior in the generation of new knowledge while larger firms are superior in their ability to appropriate returns from these innovations.

Third, and related to this second point, exploration precedes exploitation. Thus, firms carrying out exploitation are those which have succeeded in finding a good idea while exploring the space of available economic knowledge. As suggested by March, we expect many firms to fail to find an idea good enough to take through to exploitation, hence the ability to innovate persistently along the chosen (or ‘discovered’) trajectory. This is consistent with the fact that industries are typically found to exhibit turbulence, independent of the level of concentration of the market structure (Davies and Geroski 2000), and with the evidence that exit declines with age (Caves 1998; Geroski 1995) and consequently—following point two—with size (Dunne et al. 1989; Dunne and Hughes 1994; Mata and Portugal 1994). It is also consistent with the fact that mobility in market shares is found to be largely independent of the direction and magnitude of industry-wide changes, i.e., independent of whether the industry expands or contracts (Caves 1998; Dunne and Hughes 1994; Davies et al. 1996). And interestingly enough, it is also consistent with the finding that entrants in the form of established, diversifying firms are more likely to survive than entrants in the form of new firms (Dunne et al. 1988).

Fourth, if the life of firms in markets is considered to be driven by the exploration and exploitation of economic opportunities, this suggests implications for firm growth patterns. While we should expect the set of firms in the explorative phase to exhibit greater variance in their growth rates over a given period of time, with the failure of many firms, because this phase is very uncertain and chaotic, we should expect those that survive this phase and move on to the exploitation phase to have known *ex post* more continuity in their growth pattern. If shifting to exploitation implies reaching the threshold beyond which dynamic economies of scale operate and lead to a pattern of persistent innovation, then growth is required until this threshold is reached. Consequently, the group of firms in the exploitation phase should be found to have a smaller variance in their growth rates

over a given period of time, since exploitation is precisely associated with less uncertainty for firms, but not necessarily an auto-correlation of the growth rates of the individual firms. Indeed, the evidence concerning Gibrat's law is mixed; it is not clear, from empirical studies, whether corporate growth rates tend to be random or correlated over time. However, there is evidence that the mean and variance of growth rates appear to decline with size and age (Evans 1987; Dunne et al. 1989; Audretsch 1991; Sutton 1997) and in a given cohort of entrant firms, while the rate of early mortality among entrants is high, the growth rate of surviving firms is also high (Audretsch 1991; Baldwin 1995). Yet, the evidence on the autocorrelation of growth rates is mixed (Contini and Revelli 1989; Wagner and von der Schulenburg 1992; Dunne and Hughes 1994; Geroski et al. 1997). In fact, the conditions under which exploration and exploitation take place, the ease with which firms can find a good idea and move on to exploitation, their security once in exploitation—all these factors might well affect the growth patterns of the different types of firms, conditioning the auto-correlation of growth rates on those conditions.

Fifth, the relative success of exploration and exploitation is not neutral for market structure. Different industry dynamics may lead to either a large number of small firms in exploration and a small number of large firms in exploitation, or the contrary. This is indeed consistent with the finding that market structure varies from one industry to another. Moreover, industry studies suggest that differences in market structure across industries are similar from one country to another, meaning that patterns of firm growth and turbulence are systematically affected by industry-specific characteristics. An important industry-specific characteristic studied in the literature is the degree to which entrant firms and established firms are able to capture the innovative opportunities (Nelson and Winter 1982; Malerba and Orsenigo 1995). This is shown to affect the degree of concentration of innovative activities, the degree of stability in the ranking of innovators and therefore market turbulence and concentration (Audretsch 1991; Breschi et al. 2000). Yet, if exploration precedes exploitation rather than being pure alternatives, the relative importance of firms in exploitation shall reflect both the extent to which 'exploitation' allows to secure flows of revenues and the degree of

success with which explorers are able to find good ideas and to transit to exploitation. In other words, our framework suggests to interpret the relative success of new firms with respect to incumbent firms not as a pure alternative, as suggested by the theory of technological regimes, but rather as the result of the properties of the dynamic patterns experienced by firms, from exploration to exploitation.

Empirical results on firm growth patterns, market turbulence and concentration, are not always easy to interpret coherently. We claim that looking at firms growth and survival patterns through the lens of innovation strategy (exploration and exploitation) provides a good framework to interpret those results coherently as well as it should prove fruitful for providing further propositions and insights about those relationships and their variance across industries. The following section describes the model.

3 The model

The aim of the model is to investigate the behavior of an economy resulting from the interaction of a potentially large number of innovative firms, with new firms entering and unsuccessful firms exiting. Firms enter and try to introduce a new product (or a new technology) into the market. This product is assumed to come with a certain market potential, i.e., a certain size of the market for this product, a certain level of sales that it can attain. Firms do not know this market potential a priori; they discover it during the process of selling their product. Thus, firms know neither whether the product they suggest is successful, nor the potential of technological improvement of the product. If the product is unsuccessful, the firm embarks on a (cost-incurring) search for a new product. Hence, the firm *explores* what could be called the "product-market space." If the product has proved to be successful and if it has shown sufficiently high market potential, the firm will start to *exploit* this technology, i.e., it will stop searching for a new one and concentrate on the production of the successful product. With that product, firms compete for market share in a market of a given size, i.e., for a given level of demand. The larger the potential of existing firms' products, the larger the share they occupy in the market and thus the lower the opportunities (i.e., potential and thus market

share) for new entrants and the lower the opportunities for existing firms to increase their potential through R&D.

The model implies that only a limited number of firms will successfully explore the existing economic knowledge. Thus, ‘exploitation’ is conditional on successful ‘exploration’ and suggests a reward, in that it puts the firm on a path with smaller risk of failure. The necessity of initial exploration is interpreted as the need for firms to test their ideas, experiment and learn how to proceed, together with the need for customers to accommodate new goods and reallocate their resources. In the model, firms can affect their chances of shifting to exploitation by their own investments, but on the other hand, this chance also depends on a number of environmental variables (which we denote ‘market level parameters’) such as the cost of exploration of available economic knowledge, market size, or the threshold necessary to shift to exploitation. We refer to the two innovation strategies as *exploring* and *exploiting innovation strategies*.

3.1 Specification of the exploration strategy

Representation of Firms. Firms i are characterized by their production capacity and their R&D intensity. The production capacity at time t expresses their size $s_{i,t}$. We assume a very simple linear homogeneous production structure with a single production factor, i.e., the level of production factors or *input* is strictly proportional to the level of *output*. Assuming that firms produce at full capacity, by choice of unit we can set $\text{input}_{i,t} = \text{output}_{i,t} = s_{i,t}$, i.e., one unit of the production factor translates directly into one unit of output. Furthermore, while input factors are the firms’ assets, their funding are the firms’ liabilities, i.e., we can set $\text{input}_{i,t} = \text{financial endowment or production capacity}$ of firm i at time t , all expressed by $s_{i,t}$. For simplicity we assume that firms can realize their sales in the period of production, i.e., they do not build up stocks. Firms’ R&D intensity ρ_i is assumed to be independent of their size (this is consistent with e.g., Cohen and Levinthal 1990; Klette and Griliches 2000) and constant over time.

Representation of the Firms’ Products. With entry, firm i is assumed to offer one *new product* on the consumer or intermediate goods market. This can be interpreted as a single product or as a technological class of a group of products. This product/technology

has a certain market potential that we denote $p_{i,t}$. The firm considers its product to be viable if it is accepted on the market. This is specified in the model by the market potential of the product of firm i at time t being larger than its production capacity or potential actual sales $s_{i,t}$, hence $p_{i,t} \geq s_{i,t}$. In the terminology of organizational ecology (e.g., Hannan and Freeman 1989) the product can be said to “occupy a viable niche.” In that case, the firm sticks with the product and does not search for a new one. However, the firm does not know the precise value of $p_{i,t}$; it discovers (explores) it during the production and marketing process. If, however, the market potential is below the production capacity for product i , i.e., $p_{i,t} < s_{i,t}$, the market potential is too low or the niche is no longer viable and the firm will embark on a search for a new product.¹ This search for a new product may also apply immediately after a firm’s entry if it realizes that the potential of its initial product was too small, i.e., it was not accepted by the market. Then the firm will not follow the initial trajectory and will embark on the search process one period after entry.

R&D process at the firm level. Firms undertake R&D to increase $p_{i,t}$. The R&D investment of firm i at time t is given by

$$\text{R\&D}_{i,t} = \rho_i s_{i,t}, \quad (1)$$

where the outcome is specified by the following R&D production function:

$$I_{i,t} = \phi_{i,t} (\text{R\&D}_{i,t})^\alpha, \quad (2)$$

$\phi_{i,t}$ being a random variable with $E(\phi_{i,t}) = 1$ that accounts for idiosyncratic shocks in the transition from R&D effort to innovation I . $\alpha \in [0,1]$ denotes R&D elasticity. Successful R&D will increase the market potential of the firm’s product $p_{i,t}$. At the same time, $p_{i,t}$ is subject to depreciation due to the introduction of competing products. Therefore the firm will engage into R&D activities to keep pace with new firms’ products. This is specified as follows:

$$p_{i,t+1} = (1 - \delta)p_{i,t} + I_{i,t}, \quad (3)$$

δ being the depreciation rate.

Firm Growth. Firms incur costs C in the production process, where

¹ The notion of viability refers to the product and not to the firm. The process of firm exit is specified below.

$$C_{i,t} = c_i s_{i,t}, \quad (4)$$

$c_i \in [0,1]$, i.e., apart from R&D costs, they incur only variable production costs. Firms are assumed to reinvest their profit and thus to increase their production capacity, i.e., their assets, and hence their output. So we have

$$s_{i,t+1} = s_{i,t} + \underbrace{(1 - c_i - \rho_i)}_{g_i^{(R)}} s_{i,t}. \quad (5)$$

It follows that the growth rate of firm i while it chooses exploration as innovation strategy, R , and selling a product is $g_i^{(R)} := (s_{i,t+1} - s_{i,t})/s_{i,t}$. Note that $g_i^{(R)}$ is independent of the firm size by specification (Hall 1987 or Evans 1987 give support for this specification). If instead of selling a product the firm is searching for a new product, it only encounters search costs sc . Then

$$s_{i,t+1} = s_{i,t} - sc. \quad (6)$$

Summarizing this specification, Eqs. 3 and 5 or 6, respectively, specify a dynamic system where the potential of a product and its actual sales can change at all t as a function of firm specific parameters. As long as the product turns out to have a large potential ($p_{i,t} \geq s_{i,t}$), the firm sticks with it, otherwise it will search for a new product.

Shift to Exploitation. If both the potential of a firm's product $p_{i,t}$ and its size $s_{i,t}$ are above a critical level² s^{rr} , the firm considers its viable product promising enough to stop exploring the technology-market space and to start to *exploit* the technology. The firm is then able to become a persistent innovator (Geroski et al. 1997 give support for this specification). The corresponding behavior will be described in Sect. 3.2.

Exit. Firms exit if their size falls below a critical level,³ $s_{i,t} < s^x$. This includes the case where firms exit due to the fact that their financial endowment does not allow them to continue their activity of production or search.

² This level is determined in the simulation process. See Sect. 4 for further description.

³ This size is determined in the simulation process. See Sect. 4 for further description.

3.2 Specification of the exploitation strategy

Once a firm decides to exploit its technology, it will stop exploring the technology-market space. According to our model, this implies that the firm has discovered the product's actual market potential. This specification of discovery is similar to Lucas (1978) or Jovanovic (1982). Our model assumes that once the firm has discovered the actual market potential of its product $p_{i,t}$, it will fully exploit this potential; in other words it will operate at the limit of its market potential. In our model, discovering the actual potential is attained by $s_{i,t}$ attaining $p_{i,t}$. This implies that for firms following an exploitation strategy, we set $s_{i,t} = p_{i,t}$.

If a firm operates at the limit of the market potential of its product, its size will evolve according to the process specified in Eq. 3. The following equation reflects this process:

$$s_{i,t+1} = (1 - \delta)s_{i,t} + I_{i,t}$$

where $I_{i,t}$ is still specified according to Eq. 2. The rationale behind this specification is similar to the one discussed above, i.e., firms compete for market share through innovation; without innovation, their market share will inevitably decrease.

At the same time, firms encounter the same costs for production and innovation as specified in Eq. 5. Taking these two processes together, the following equation specifies the dynamics for firms' sizes in exploitation as a function of their costs and their innovation outputs:

$$s_{i,t+1} = (1 - \delta)s_{i,t} + (1 - c_i - \rho_i)s_{i,t} + \phi_{i,t}(\rho_i s_{i,t})^\alpha \quad (7)$$

So that the growth rate of firm i in exploitation, T , is

$$g_i^{(T)} = (1 - c_i - \rho_i - \delta) + \phi_{i,t}(\rho_i)^\alpha s_{i,t}^{(\alpha-1)}. \quad (8)$$

For $\alpha = 1$, this equation simplifies to

$$E(g_i^{(T)}) = (1 - c_i - \delta) \quad (9)$$

which is independent of the size of firm i (unlike the growth rate given in Eq. 8). Hence, as Eqs. 5 and 9 make evident, firms with different innovation strategies differ in their growth rates.

Once the firm has decided to carry out exploitation, it does not switch back to the exploration strategy. In exploitation, firms are subject to the same exit rule as given above, i.e., they exit if $s_{i,t} < s^x$, s^x

being identical for both innovation strategies. Moreover, we specify the R&D-process in exploitation exactly the same as in exploration (Eqs. 1 and 2).

4 Simulation study

4.1 Methodological approach

The objective of the article is to study the aggregate behavior of a undetermined and varying number of heterogeneous firms within a market characterized by different and changing parameter settings.

Firms are heterogeneous, i.e., they can differ in their individual innovation strategy and their resulting growth or exit patterns. Since a large number of firm level processes—entry, the growth and decline of firms conducting R&D with different innovation strategies and exit—happen simultaneously and are interlinked, we do not model the aggregate behavior analytically. Rather, we implement the structural model suggested in Sect. 3 in a simulation-based framework and analyze the impact of the market level variables on the basis of a sensitivity analysis.

The principal approach is to vary each of the market level variables within ranges that are specified below, leaving the others constant. This allows for an isolated analysis of the impact of each of these variables. In order to obtain statistically viable results, we vary each of the variables with small increments and run each variable setting three times. Thus, the simulation model has been run 1,512 times (with 600 iteration steps each). Figure 5 (which is discussed in detail below) illustrates the result of this approach.

From these simulation runs, we derive a number of testable hypotheses. For some of these, empirical evidence can be found in the existing body of literature. This literature will be quoted where appropriate. The other propositions are theoretical in nature and are suggested for future empirical research. Again, since with the approach chosen here we can access the data generating process at any level of the analysis, our approach allows to investigate a large number of phenomena. So the propositions given here are only a subset of the number of possible ones.

Our economy consists of an arbitrary number of firms that enter according to a Poisson process (Audretsch 1995; Siegfried and Evans 1994 give

support for a specification with constant entry rates). These firms differ in three parameters when they enter the market: their start-up size $s_{i,t}$, the potential of their product $p_{i,t}$ and their R&D intensity ρ_i .

Firms draw their entry size $s_{i,t}$ from a lognormal distribution $\text{LN}[1,1]$. Firms' R&D intensity ρ_i (which remains constant over time) is drawn from a lognormal distribution that is specified such that 99% of firms' R&D intensity is below 10%. The random variable that accounts for innovation success, $\phi_{i,t}$, is drawn from a uniform distribution $\text{U}[0,2]$. Variable costs are set at $c_i = 0.8$ for all firms. The R&D-elasticity is set at $\alpha = 1$.

The market potential of the product of a firm i that enters in iteration step t , $p_{i,t}$, is determined as a random share of the remaining level of demand in the market (or remaining market size) at time t . The entering artificial firms draw their random share from a joint uniform distribution that is specified such that the expected value of the share of each firm is the same for each entry cohort. Note, however, that this expected value can differ at each iteration step, i.e., for each entry cohort, as a function of the remaining market size. Similarly, the evolution of firm i 's potential after startup through innovation (according to Eq. 3) is such that an increase can only capture shares of the remaining share of the market size. Contrary to the random distribution at start up, the relative increase in potential corresponds to the relative innovation success (specified by Eq. 2). This specification has a twofold advantage. First, it captures a real life phenomenon, namely the fact that the market penetration of a new product depends not only on its technical specification but also on the purchasing power of consumers that is dedicated to this product. Second, it avoids computational overflow.

This specification implicitly introduces early mover advantages, i.e., early entrants will be able to introduce products with a larger potential. This is due to the fact that at an early stage in the evolution of a market, the unserved demand in the market is larger. However, given the process described above (Eq. 3), this potential might decrease over time, since the remaining purchasing power of the market increases when firms exit, as this exit leads to the release of the purchasing power dedicated to its product. The disadvantage of this specification is that we cannot investigate the interaction between innovation and purchasing power dedicated to the respective market. We suggest this for further research. Following

Hannan and Freeman (1989, p. 100), we refer to the market size as the *carrying capacity* of the market.

In the following sections, we will present the results of a number of simulation runs of the model. We will first (Sect. 4.2) present results that the model will generate by specification i.e., results that are common for all simulation runs even with different parameter settings. Here, we will also investigate the consequences of different realizations of parameters on the level of the firm. In Sect. 5, we investigate the impact of parameters on the market level, i.e., parameters that are identical for all firms.

4.2 Stylized facts that the model is able to reproduce

Firm size distribution and its evolution. For this set of simulation runs, the carrying capacity of the market has been set to 20,000.⁴ Figure 1 reproduces the firm size distribution of the simulation after 600 iteration steps. The resulting distribution corresponds to empirically observable patterns of size distributions, i.e., size distributions that are skewed to the right. Taking the log of the data, the distribution can be approximated by a normal distribution (right-hand side of Fig. 1). Figure 2 shows the evolution of the number and mean size of firms. It can be seen that the number of firms stabilizes above 500 under the given parameter settings. The mean size converges to a value of around 40. These figures are of course dimensionless, i.e., they should be interpreted with respect to the carrying capacity (which is set to 20,000) and not compared with real-life units of measurement. Figure 3 reproduces the evolution of the second and third moment of the firm size distribution. For the analysis of the standard deviation, the data have been transformed with the log function to investigate the relation to the lognormal distribution. Indeed, the standard deviation fluctuates slightly above one. Also, the skew of the distribution of the logged data fluctuates around a value slightly above 0, as the right hand side of Fig. 3 illustrates. Thus, the size distribution generated by the model is very similar to the type empirically observed (Simon and Bonini 1958; Ijiri and Simon 1977; Lucas 1978;

Audretsch 1995; Sutton 1997; Cabral and Mata 1996; Geroski 1998), i.e., a firm size distribution that is skewed to the right. As will become evident later, this persistent distribution emerges despite the fact that the underlying firm demographic processes are turbulent: firms enter at any time, they grow, others shrink in size while yet others exit from the market. Hence, there is a persistent change in the rank order of firms. Davies et al. (1996) and Dunne et al. (1989) provide evidence for these phenomena. We take these findings of the model as first evidence that our model does not generate biased results.

Entry vs. exit. A persistent result from the model is that entry and exit are strongly correlated, independent of the actual parameter settings (Dunne et al. 1988; Cable and Schwalbach 1991; Siegfried and Evans 1994; Caves 1998 provide empirical evidence for this finding). Entry shocks translate into temporarily higher net entry, which quickly falls, however, and turns into net exit once the entry shock is over (see Fig. 4).⁵ This net exit steadily decreases and the number of firms falls back to the pre-shock level, so that the (artificial) economy completely absorbs this entry shock.

This result seems to be highly relevant within the context of the increasing political effort to promote the creation of new firms. If the aim of these efforts is to reduce unemployment, they will be useless if they also force other firms to exit.⁶ One explanation may be that successful entering firms will reduce the chance for incumbent firms to find a new successful product given constant carrying capacity of the market. To our knowledge, there is no systematic investigation of this crowding-out effect. We suggest this for further research.

5 Implications of variations in market level parameters

In this section we present results obtained from the variation of parameters that affect all firms in the

⁴ Variations in this value do not modify the following findings but lead to a larger number of iteration steps until firm size distribution stabilizes.

⁵ For the generation of this realization, we assumed demand in the market to be growing. Otherwise an entry shock translates into an immediate exit shock such that net entry still fluctuates around 0.

⁶ Here, we do not consider structural changes (such as an increase in the overall R&D intensity) that are caused by these activities.

Fig. 1 Histograms of firm size distribution after $t = 600$ iteration steps. Logs are reproduced on right hand side

Fig. 2 Evolution of number of firms in the market at time t (left) and their mean size (right)

Fig. 3 Evolution of standard deviation (left) and skewness (right) of the Log of the firm size distribution

Fig. 4 Net entry (entry–exit). Left: implication of an entry shock (which occurs at $200 \leq t < 300$). Right: alternative run without entry shock

sample simultaneously, i.e., parameters on the *market level*. The parameters to be investigated are related to market size and to the difficulty of finding or keeping a viable innovation (i.e., a viable niche). We also consider the effect of varying the firm level parameters that have been investigated in Sect. 4.2 for all firms simultaneously. Table 1 lists the parameters that are varied in these simulations.

We analyse the impact of these parameters on nine firm-demographic variables: average age, average firm size, standard deviation of firm size, average

number of firms, entropy index, rank-order turbulence, share of firms in exploitation, their aggregate market share, and the average age of firms that move to exploitation.

5.1 Specification of the simulation

In varying these parameters and running simulations, we choose a Monte-Carlo approach to analyze the properties of the system modeled by Eqs. 1–7. The simulations have been run using Mathematica. It is in

Table 1 Parameters used in simulations

Parameter	Lower bound	Upper bound	Increment
Carrying capacity, CC	5,000	50,000	5,000
Growth rate of CC	0.005	0.035	0.005
Mean of startup size μ_s	0.1	1	0.1
Mean of market potential μ_p	1	10	1
Share of firms with R&D	0.1	1	0.1
Depreciation rate δ	0.01	0.09	0.01
Search costs	0.05	0.8	0.05

this possibility of varying parameters of interest that cannot be easily varied in real life economies and investigating the consequences that simulation approaches show their full advantages. Figure 5 and Table 2 show the impact of the variation of these parameters on firm demographic variables. We derive the propositions from the correlations presented there. Each dot in Fig. 5 represents the result of one simulation run, where the parameter under consideration has been varied while the other parameters—such as distribution of R&D intensity, parameters of entry process etc.—have been kept constant. Let us now discuss these results.

5.2 Market size, carrying capacity

In order to analyze the effect of market dynamics on the firm-demographic variables mentioned above, we chose two approaches. *First*, we kept the level of the market size constant during each respective simulation run, but letting it vary from 5,000 to 50,000 by steps of 5,000, running three simulations for each value. This approach is rather “comparative static”⁷ since the market size does not increase nor decrease within a simulation run. Think of *market size* as sales in an industry or even as GDP in an economy. Hence, it also expresses demand and firms compete for this demand with their products. From this background, this notion of sales is closely related to the notion of *carrying capacity* (Hannan and Freeman 1989).

Second, we chose a small initial market size and let the market grow linearly with each iteration step by rates varying from 0.5% to 3.5%. This sheds light on the effects obtained when markets grow. It is useful to think of the first case as mature markets with

settled demand structure and of the second case as young markets with increasing demand.

While varying these market size parameters, other parameters—such as distribution of R&D intensity, parameters of entry process etc.—have been kept constant. Each simulation has been run over 600 iteration steps, which is a value that allows the variables to stabilize. The first two columns of Table 2 and Fig. 5 represent the outcome of these simulation runs. A few interesting observations emerge from this first set of simulations.

Market size. In the first set of simulations, we find that with increasing market size, the number of firms increases up to a maximum level. At the same time, their average size as well as the variance in firm size (expressed by the standard deviation) increases. At the same time, the age of firms increases. Larger markets lead to a fall in the age at which firms move to exploitation. At the same time, the share of firms with a viable product increases, as does their market share.

Growth rate of market. In the second set of simulations, i.e., for “dynamic markets,” we find similar results with two interesting exceptions: a higher growth rate of markets leads to lower firm size on average, but also with lower variance. The share of firms in exploitation as well as their market size decreases. From these findings, we derive the following propositions:

Proposition 1 Larger markets can accommodate a larger number of firms. On larger markets the number of small firms will increase more than proportionally. At the same time the size of the largest firms will increase more than proportionally.

These findings follow from the correlation of *market size* and *growth rate* with *average firm size*, *standard deviation of firm size* and *average number of firms*. Both parts of this proposition have been analyzed in the

⁷ In this context, the concept might of course be misleading, since we do not refer to the textbook notion of static models.

Fig. 5 Effect of the variation of different market level parameters on firm-demographic variables

literature. Lucas (1978, Table 1) finds that larger markets (expressed as GDP, using US data from 1900 to 1970) will indeed have a positive impact on average firm size. He estimates the elasticity to be slightly below unity, hence a 1% increase in GDP implies a 1% increase in average firm size, thus giving support for Proposition 1. These findings seem highly relevant in the context of European integration: larger markets leading to larger firms implies that since European integration increases the market size, it also increases the tendency to undertake mergers.

Proposition 2 The larger a market, the more favorable it is for survival of firms.

This proposition is derived from the simple correlation of *market size* and *growth rate* with the *average age* of firms. Using a sample of 11,000 young US manufacturing firms, Audretsch and Mahmood (1994) find that the likelihood of survival

of these firms is positively influenced by market growth, thus giving support for this hypothesis.

Proposition 3 The larger a market, the easier it will be for firms to find a viable product.

This proposition is derived from the finding that the average age for moving to exploitation decreases while the share of firms in exploitation and their market share increases with market size. We are not aware of any empirical study that investigates this relationship between market size and the type of product. This is certainly due to the fact that the notion of “viability” is not easy to capture empirically. We suggest this proposition for further research.

Proposition 4 The stronger the growth rate of the market, the easier it will be for firms to find a viable product but also the larger the number of firms in search of a viable product (firms in exploration).

Table 2 Correlation of market level parameters and firm-demographic variables

	MarkSize	GRMarket	StartUpS	Potenti	RDSHare	Delta	SearCost
Average age (<i>p</i> -values)	0.683 (0.000)	0.990 (0.000)	0.975 (0.000)	0.965 (0.000)	0.935 (0.000)	-0.980(0.000)	-0.798 (0.000)
Average firm size (<i>p</i> -values)	0.973 (0.000)	-0.848 (0.000)	0.892 (0.000)	-0.753 (0.000)	-0.879 (0.000)	0.845 (0.000)	0.956 (0.000)
SD of firm size(<i>p</i> -values)	0.689 (0.000)	-0.891 (0.027)	-0.482 (0.000)	-0.859 (0.000)	-0.837 (0.000)	0.867 (0.000)	0.896 (0.000)
Average number of firms (<i>p</i> -values)	0.819 (0.000)	0.997 (0.000)	-0.853 (0.000)	0.972 (0.000)	0.924 (0.000)	-0.967 (0.000)	-0.863 (0.000)
Entropy index (<i>p</i> -values)	-0.816 (0.000)	-0.993 (0.000)	0.721 (0.000)	-0.971 (0.000)	-0.941 (0.000)	0.975 (0.000)	0.799 (0.000)
Turbulence (<i>p</i> -values)	-0.720 (0.000)	-0.614(0.001)	-0.093 (0.690)	-0.722 (0.000)	-0.308 (0.097)	0.978 (0.000)	0.824 (0.000)
Share of explt. (<i>p</i> -values)	0.891 (0.000)	-0.673 (0.630)	-0.112 (0.000)	-0.786 (0.000)	-0.772 (0.000)	0.900 (0.000)	0.618 (0.000)
Market share of explt. (<i>p</i> -values)	0.728 (0.000)	-0.889 (0.265)	-0.255 (0.000)	-0.979 (0.000)	-0.903 (0.000)	0.702 (0.000)	0.121 (0.396)
Av. age to explt. (<i>p</i> -values)	-0.763 (0.000)	-0.610 (0.002)	-0.568 (0.007)	-0.926 (0.000)	0.526 (0.003)	-0.801 (0.000)	0.924 (0.000)

Note: *p*-values indicate probabilities of correlations to be insignificant, derived from a two-sided *t*-test

This proposition is derived from the negative correlation of (market) share of firms in exploitation and the average age of firms when they switch from exploration to exploitation. However, the problem with respect to empirical research, discussed with respect to Proposition 3, remains.

The findings of this section and of Sect. 4.2 can be summarized as follows: the larger the market or the growth rate of this market, the larger the growth and innovation opportunities, and the larger the success of young firms. Thus the success of these firms is *demand driven*. From this point of view, a mere increase in firm creations cannot be considered a success unless it is accompanied by an increase in demand. Policies to increase business creation should rather target market size (e.g., through deregulation or the elimination of trade barriers) instead of just considering firm creations per se to be a success.

5.3 Effects of the pace of innovation and the “ease of innovation”: depreciation rate of innovation and costs of search for new product

The concept of “ease of innovation” is difficult to capture empirically. It is linked to the notion of industry life cycle (Gort and Klepper 1982; Klepper 1996), where in early phases of this life cycle the economic opportunities are abundant and a large number of firms is engaged in exploring them. At this stage, it is relatively easy to introduce an innovative product. In more mature stages of the life cycle, where typically a dominant design has emerged, this is more difficult. This process can potentially have a large impact on the demography of innovating firms: in a market where it is difficult to find a new product or difficult to keep the income from a new product due to high innovation pressure from other firms, we expect more turbulence in market shares and faster exiting of firms. We consider two parameters that express these dynamics, “Delta,” which captures innovation pressure through depreciation of existing products and “Search Costs.” The final two columns of Fig. 5 and Table 2 reflect the impact of these parameters. We discuss them in turn.

Delta, δ . This parameter specifies *depreciation* of the products’ potential or of firms’ market share (as specified in Eqs. 3 and 7). Technically speaking, this parameter reduces the potential of a product of a firm

in exploration (from Eq. 3) or the size (i.e., sales) of a firm in exploitation (from 7). With this parameter we aim to describe the *pace of innovation* and thus the competition that emerges from other innovators: the stronger this competition, the larger the depreciation rate δ since consumers switch their demand more quickly to other products, i.e., to other firms.

The impact of this parameter can be described as follows. With increasing δ (i.e., with increasing competition), the average age of firms and their average number both decrease. The average firm size and its standard deviation increase with δ . The time needed to find a viable product decreases, as does the share of firms with such a product and their market share. The variation in the rank of market shares (turbulence) increases. We derive the following propositions from these findings:

Proposition 5 Higher pace of innovation will decrease average lifetime of firms.

Given the findings of Sect. 4.2 we conclude that increasing competition will primarily affect firms with lower potential and lower start-up size. Hence, firms with larger potential can expand their potential even more quickly, since demand is more highly concentrated on these firms. In our model, this implies that firms will switch to exploitation more quickly, i.e., that incumbent firms will find a viable product more easily. This leads us to the following proposition.

Proposition 6 Higher pace of innovation will increase average firm size

The intuition behind this proposition is that competition due to a high pace of innovation will cause weak firms to exit more quickly, and the demand for their products will be released for reallocation. Then, remaining firms will find a viable product more easily and have larger opportunities to expand. In turn, the market more quickly becomes characterized by a small number of firms with established products. Hence

Proposition 7 Higher pace of innovation will increase selection pressure and dominance of established technologies.

Nelson and Winter (1982, Chaps. 12 and 13) find a similar outcome in their model. However, we are not aware of any empirical evidence for these propositions. We suggest the investigation of Propositions 5–7 for further research.

Search costs (sc). As expressed in Eq. 6, firms encounter search costs when they explore the product market space for a new technology. The larger these search costs, i.e., the more expensive the search process, the faster the financial resources of the firms will be exhausted, increasing the probability of exit. Hence, search costs can be considered as a proxy for the ease of finding a new viable product and thus for *innovation opportunities*.

The last columns of Fig. 5 and Table 2 show the effect of variations in these search costs. The following results are of interest: with increasing search costs, the number and age of firms declines while average firm size and standard deviation increase. The average age at which firms shift to exploitation increases with search costs. This also applies for the share of exploiting firms and their market share. This leads us to the following propositions:

Proposition 8 Higher search costs, hence a lower level of innovation opportunities, lead to a stronger shakeout of firms and a longer time needed to find a viable product.

This first part is true by definition of search costs. The intuition behind the second part is that firms will have more difficulty in finding viable products when search costs are high. If we interpret Proposition 8 in the opposite direction, we obtain

Proposition 9 If innovation opportunities are high, the industry will be characterized by a large number of small firms.

This proposition seems intuitive, however, we are not aware of any empirical analysis on this question. This proposition is therefore left for further research.

5.4 Findings on market concentration and demographic turbulence

Starting from a more general perspective, we now derive a set of propositions concerning the effects of market level parameters on market concentration and on variations in the rank order of firms (i.e., on turbulence). Here, we will discuss the joint effects of several parameters simultaneously.

It can be seen (from Table 2 and Fig. 5) that concentration (measured by an entropy index) is significantly correlated with all of the market level parameters. The same applies to a measure of

turbulence,⁸ with the exception of start-up size, which does not seem to influence turbulence. It is also noticeable that the sign of the correlation of market level parameters with both concentration and turbulence are similar. Hence, by reverse conclusion, concentration and turbulence are positively correlated. Davies and Geroski (2000) provide empirical evidence that supports this finding.

We see from Table 2 and Fig. 5 that bigger market size and higher growth rates of market size lead to decreasing levels of concentration. Hence

Proposition 10 Larger markets accommodate a larger number of firms (Proposition 1), therefore larger markets will display lower levels of concentration.

This proposition is especially interesting in connection with Proposition 1. Thus, larger but static markets (MarkSize) accommodate a larger number of firms that are also of larger size, on average. Given that the standard deviation of firm size increases with market size as well, we conclude that the concentration level decreases due to the fact that even in mature markets with a static market size the number of small firms increases more than proportionally (see the discussion of Proposition 1.) This effect is even stronger in young markets, i.e., when the market grows over time (GRMarket). Here, with increasing growth rate, the market is more and more dominated by an increasing number of small firms, hence concentration decreases.

The effects are slightly different for innovation-oriented parameters. A higher pace of innovation (Delta) increases concentration. In connection with Propositions 6 and 7 we hypothesize that concentration increases, since the higher pace of innovation leads to stronger shakeout. For search costs, based on Propositions 8 and 9, the effects are similar.

Interpreting increasing market size as well as increasing pace and cost of innovation as raising selection pressure, we derive

Proposition 11 Increasing selection pressure leads to an increase in market concentration and to an increase in market turbulence.

Although this proposition is rather intuitive, we are not aware of any empirical study that points in this

direction. The second part of this hypothesis follows from the fact that in the simulations, concentration and turbulence vary in the same direction (Davies and Geroski 2000).

Interpreting the findings of the model in the opposite direction, we suggest the use of high levels of rank order turbulence and/or concentration as proxies for markets with high selection pressure in empirical research.

6 Summary and conclusion

The aim of this article has been to develop a model that explicitly considers the interaction of firm demographic processes, innovation strategies and market structure. For this purpose, we specify a structural model of firm growth where growth is driven by reinvestment of profits, which in turn depends on firms' R&D intensity and on the costs of search for a new product. Firms can follow different innovation strategies, i.e., they can explore the technology space in the search for a new technology or they can exploit existing technological trajectories. While we associate the search for a "viable product" with the first innovation strategy, the latter is associated with the firm actually offering such a product. Firms can switch their innovation strategy from exploration to exploitation.

Firms are characterized by their size and a set of variables that are related to innovation. However, the growth of firms depends not only on these parameters, but also on the interaction with other firms, which in the model is mainly driven by competition for a limited purchasing power. In the model, firms are boundedly rational, the number of firms is potentially illimited and we do not impose limit states such as an optimizing equilibrium or a priori given limit distributions. In that sense, the model is microfounded and represents an inductive approach.

We use a simulation-based approach to derive a number of empirically testable hypotheses on the basis of this model. On the one hand, we are able to derive a set of propositions that have found empirical support in the literature. We take these propositions as evidence in favor of the explanatory power of the model. Moreover, the model shows implicitly that the aggregate regularities of market structures are consistent with the dynamic coexistence of firms engaging in exploration and exploitation of economic

⁸ Turbulence is measured as the variance of the rate of change of market shares.

opportunities. On the other hand, we go beyond this literature, suggesting a set of propositions on the relation between firms' demographic processes, firms' innovative behavior and market structure that have not yet been investigated and that we suggest for further empirical research.

The approach has shown that firms' innovative strategies affect market structures. The model suggests that the reason why firm size distribution is skewed, meaning that there is a persistent asymmetry of firm sizes and a predominance of small firms, is that firms explore the space of economic opportunities before they are able to exploit some profitable avenue. This necessity of initial exploration can be interpreted as the necessity for firms to test their ideas and learn how to proceed, as well as the necessity for customers to accommodate new goods and reallocate their resources. Then, small entrants have to grow in order to survive. Thus, among the small firms in the tail of the distribution, a few will grow enough to become exploiters and many will fail. The skewed firm size distribution thus reflects this dynamics of exploration and exploitation.

The model provides evidence that market concentration is positively correlated with turbulence in the rank order of firms. The correlation is in fact generated by the relation of both variables with the intensity of competition. Put differently: the stronger the competition, the higher the level of turbulence and firm concentration. Indeed, more intense competition implies that competitive advantages vanish more quickly, but as explorers might have the supplementary burden of searching for a new product while exploiters follow a specific trajectory, more competition implies on average more selective pressure on the explorers than on the exploiters. Hence, the share of exploiters increases with the intensity of competition. This in turn is an outcome that contradicts standard results, according to which concentration is due to a lack of competition. Hence, the model suggests that a rise in the concentration level does not conflict with more intensive competition between large firms.

Apart from these findings, we believe that our approach has made a methodological contribution. With the method suggested here, we are able to access the data generation process at any level of the analysis and therefore test existing hypotheses that are difficult to test with existing data. We are also

able to derive new hypotheses based on variations in the parameters involved, which we suggest for further research. The number of possible hypotheses is not limited a priori, and the hypotheses suggested here are only a fraction of those that could be proposed on the basis of our model.

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