Simulating knowledge dynamics in innovation networks (SKIN)

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Abstract

An agent-based simulation model representing a theory of the dynamic processes involved in innovation in modern knowledge-based industries is described. The agent-based approach allows the representation of heterogeneous agents that have individual and varying stocks of knowledge. The simulation is able to model uncertainty, historical change, effect of failure on the agent population, and agent learning from experience, from individual research and from partners and collaborators,. The interactions between the agents occur on two levels: through a market with firms supplying and consuming goods for a price, and through the exchange of knowledge. A brief description of the implementation of the model and its user interface is given.

1. Introduction

Although the institutional approach in economics has introduced a sociological perspective to mainstream economic theory, sociologists such as Granovetter (1985), Willke (1995), Schneider and Kenis (1996), Weyer (2000) and others have criticised the approach, arguing that actual markets are shaped by social factors to a much larger degree than institutional economics allows. 'Social shaping' not only refers to the fact that real markets rely on the co-operative behaviour of their members, that is, on the institutional regulations that frame the interactions of the traders, but also refers to an equally important aspect, the social role of the networks of collaborations and contracts which are an integral part of most markets. Modern innovation economics, as framed in evolutionary economics, is considering the various dimensions that are shaping the organization of innovation processes in knowledge intensive industries.

Networks are a principal mode of co-ordination which are particularly relevant in knowledge-based market sectors such as biotechnology and the ICT industries. The need for knowledge creation and transfer within markets is one of the main reasons for networking. Powell (1990: 304) suggests that it is impossible to put a price tag on qualitative features such as an innovation-friendly strategy, a special style of

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production, technological capacity, know-how or a zero-failure philosophy, none of which can be traded on the market. Combining knowledge resources in networks enables innovation and learning that are difficult to provide by other means (Summerton 1999). "In innovation networks, inter-organisational communications negotiate the features of new technologies and integrate user contexts. Joint agendas and sometimes implementations generate various feedbacks of learning and innovation which reflect on the planning process" (Krohn 1995: 29). Thus, markets are more than places where goods are bought and sold within an institutional context: they are the arenas where innovation takes place, where knowledge is generated, communicated, re-combined and exchanged. The SKIN model to be described in this chapter aims to combine a sociological perspective with insights from evolutionary economics in order to characterise both the trading and the knowledge levels of high-tech innovation networks.

2. The model

SKIN is a multi-agent model containing heterogeneous agents which act in a complex and changing environment. Its agents are innovative firms who try to sell their innovations to other agents and end users but who also have to buy raw materials or more sophisticated inputs from other agents (or material suppliers) in order to produce their outputs. This basic model of a market is extended with a representation of the knowledge dynamics in and between the firms. Each firm tries to improve its innovation performance and its sales by improving its knowledge base through adaptation to user needs, incremental or radical learning, and co-operation and networking with other agents. In the next paragraphs, the elements and processes of the model are described in further detail.

2.1. The agents

A SKIN agent is a firm with an individual knowledge base. This knowledge base is called its *kene* (Gilbert 1997) and consists of a number of "units of knowledge". Each unit is represented as a triple consisting of a firm's *capability C* in a scientific, technological or business domain (e.g. biochemistry), represented by an integer randomly chosen from the range of 1..1000, its *ability A* to perform a certain application in this field (e.g. a synthesis procedure or filtering technique in the field of biochemistry), represented by an integer randomly chosen from the range 1..10 and the *expertise level E* the firm has achieved with respect to this ability (represented by an integer randomly chosen from the range 1..10). The firm's kene is its collection of C/A/E-triples.

Figure 1: The kene of a firm

$$\left\{ \begin{array}{c} C \\ A \\ E \end{array} \right\}, \left\{ \begin{array}{c} C \\ A \\ E \end{array} \right\}, \left\{ \begin{array}{c} C \\ A \\ E \end{array} \right\}, \left\{ \begin{array}{c} C \\ A \\ E \end{array} \right\}, \left\{ \begin{array}{c} C \\ A \\ E \end{array} \right\}, \dots$$

When it is set up, each firm has a stock of initial *capital*. It needs this capital to produce for the market and to improve its knowledge base, and it can increase its capital by selling products. The amount of capital owned by a firm is a measure of its

size and also influences the amount of knowledge that it can support, represented by the number of triples in its kene.

Most firms are initially given a standard amount of starting capital, but in order to model differences in firm size, a few randomly chosen firms can be given extra capital (set using the "n-big-firms" slider on the interface - see Figure 5).

2.2.   The market

Firms apply their knowledge to create innovative products that have a chance to be successful in the market. The special focus of a firm, its potential innovation, is called an *innovation hypothesis*. In the model, the innovation hypothesis (IH) consists of a subset of the firm's kene triples.

Figure 2: Forming an innovation hypothesis

IH = (1, 3, 4)
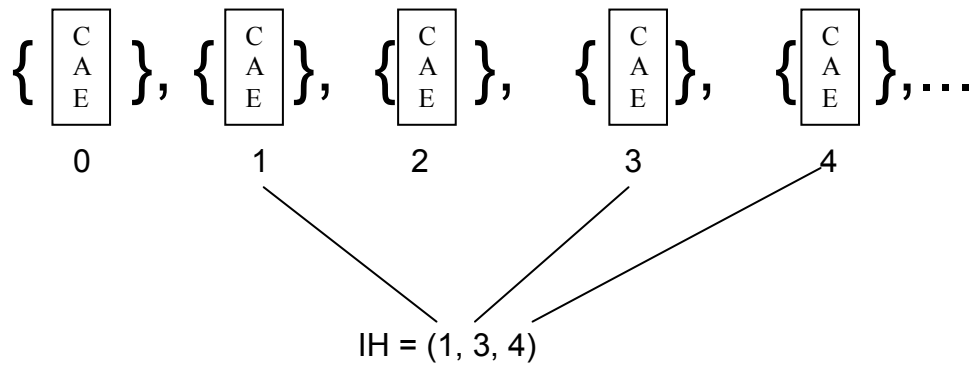
The underlying idea for an innovation, modelled by the innovation hypothesis, is the source an agent uses for its attempts to make profits on the market. Developing the innovation hypothesis into a *product* is a mapping procedure where the capabilities and abilities of the innovation hypothesis are used to compute an index number that represents the product.

A firm's product, *P*, is generated from its innovation hypothesis as

$$P = (C_1 * A_1) + (C_3 * A_3) + (C_4 * A_4) + \ldots \text{ modulus } N \qquad (1)$$

(where *N* is the total number of products ever possible within the model)

The product has a certain *quality* which is also computed from the innovation hypothesis in a similar way, but using a product of the abilities and the expertise levels for each triple in the innovation hypothesis.

In order to realise the product, the agent needs some raw materials or more sophisticated inputs from other agents. What exactly it needs is also determined by the underlying innovation hypothesis: the kind of material required for an input is obtained by selecting subsets from the innovation hypotheses and applying the standard mapping function (equation 1).

These inputs are chosen so that each is different and differs from the firm's own product. In order for an agent to be able to engage in production, all the inputs need

to be available on the market, i.e. provided by other agents. If the inputs are not available, the agent is not able to produce and has to give up this attempt to innovate. If there is more than one supplier for a certain input, the agent will choose the one at the cheapest price and, if there are several similar offers, the one with the highest quality.

Figure 3: A firm's input requirements

$$IH = \left\{\begin{matrix}C\\A\\E\end{matrix}\right\}\left\{\begin{matrix}C\\A\\E\end{matrix}\right\}, \quad \left\{\begin{matrix}C\\A\\E\end{matrix}\right\}\left\{\begin{matrix}C\\A\\E\end{matrix}\right\}\left\{\begin{matrix}C\\A\\E\end{matrix}\right\},\ldots$$

Input 1: $(C_1 * A_1 + C_2 * A_2)$ modulus N
Input 2: $(C_3 * A_3 + C_4 * A_4 + C_5 * A_5)$ modulus N

If the agent can go into production, it has to find a price for its own product which takes account of the input prices it is paying and a possible profit margin. While the simulation starts with assuming that all agents have a product that they can sell and with the product prices set at random, as the simulation proceeds, a price adjustment mechanism ensures that the selling price will at least equal the total cost of production.

An agent will then buy the requested inputs from its suppliers using its capital to do so. It produces its output and puts it on the market in the next round. Agents follow a standard pricing strategy such that if a product sells, its price will be increased in the next round, while if it does not sell, the price is reduced each round, until the cost of production is reached. In this way, agents are able to adapt their prices to demand.

In making a product, an agent applies the knowledge in its innovation hypothesis and this increases its expertise in this area. This is the way that *learning by doing/using* is modelled. The expertise level of the triples in the innovation hypothesis is increased by 1 and the expertise levels of the other triples are decremented by 1. Unused triples in the kene eventually drop to an expertise level of 0 and are deleted from the kene; the corresponding abilities are "forgotten".

2.3. The environment

Within the model, there are two world settings for the agents' environment. With the first, the model represents a closed market in which the agents trade only with each other as equals, sharing the same attributes and rules (see above). Each agent buys its inputs from other agents and itself produces an output which must then be bought by other agents (as part of their input requirements). The alternative world is a market where external sources and purchasers interact with the firm population. With this setting, the model includes some supplier firms and some customer firms. The supplier firms try to sell "raw materials", i.e. the basic elements necessary for the production of goods, to the other firms, but they do not buy anything. The customer firms are 'end users' who buy products without producing anything themselves. The

implementation of the model allows for switching between these settings in order to experiment with the two market conditions (see the 'open-system' slider in Figure 5).

2.4.   Learning and co-operation: improving innovation performance

In trying to be successful on the market, the firms are highly dependent on their innovation hypothesis, i.e. on their kene. If a product does not meet any demand, the firm has to adapt its knowledge in order to produce something else for which there are customers. In the model, a firm can choose between different ways of improving its performance, either alone or in co-operation, and either in an incremental or in a more radical fashion. All strategies have in common that they are costly: the firm has to pay a "tax" as the cost of applying an improvement strategy.

2.4.1. Incremental research

If a firm's previous innovation has been successful, i.e. the profit it gained was larger than a certain success threshold, the firm will continue selling the same product in the next round. However, if the previous profit was below the threshold, it considers that it is time for change. If the firm still has enough capital, it will carry out incremental research (R&D in the firm's labs). Performing incremental research means that a firm tries to improve its product by altering one of its abilities chosen from the triples in its innovation hypothesis while generally sticking to its focal capabilities. This is to exploit the action space available for a certain capability. The ability in each triple is considered to be a point in the respective capability's action space. To move in the action space means to go up or down by 1 on the integer scale, thus allowing for two possible incremental "research directions". Initially, the research direction of a firm is set at random. Later it learns to adjust to success or failure: if a move in the action space has been successful the firm will continue with the same research direction within the same triple; if it has been a failure, the firm will randomly select a different triple from the innovation hypothesis and try again with a random research direction on the triple´s ability.

Figure 4: Incremental research
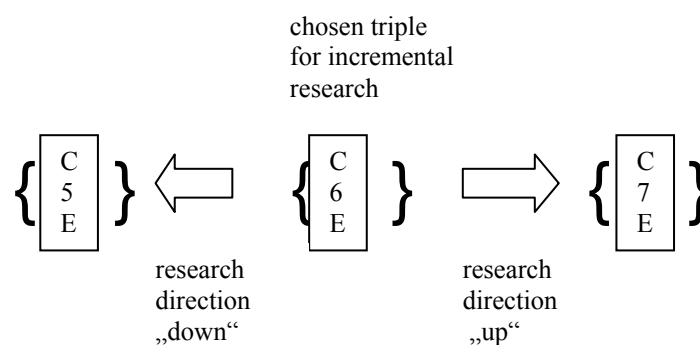
2.4.2. Radical research

A firm under serious pressure that is in danger of becoming bankrupt will turn to more radical means in order to prevent its exit from the market. In this situation, a firm can choose to perform radical research to explore a completely different area of market

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opportunities. In the model, an agent under financial pressure turns to a new innovation hypothesis after first "inventing" a new capability for its kene. This is done by randomly changing one capability in the kene for a new one and then forming an innovation hypothesis from its kene set.

2.4.3. Partnerships

An agent in the model may consider partnerships (alliances, joint ventures etc.) and networks in order to learn from other agents, i.e. to exploit external knowledge sources. Within the model we can switch between a scenario where partnerships and networks are prohibited and a scenario where they are allowed (see Figure 5, slider "collaboration"). In the latter scenario, the decision whether and with whom to co-operate is based on mutual observations of the agents. The information a firm can gather about other agents is provided by a marketing feature: to advertise its product, a firm publishes the capabilities used in its innovation hypothesis. The firm's advertisement is then the basis for decisions by other firms to form or reject co-operative arrangements.

In experimenting with the model, we can choose between two different partner search strategies, both of which compare the firm's own capabilities in its innovation hypothesis and the possible partner's capabilities as seen in its advertisement. Applying the conservative strategy, a firm will be attracted by a possible partner who has similar capabilities; using a progressive strategy the attraction is based on the difference between the capability sets (see Figure 5, slider "partnership-strategy").

Previously good experience with former contacts generally augurs well for renewing a partnership. This is mirrored in the model: to find a partner, the firm will look at previous partners first, then at its suppliers, customers and finally at all others. If there is a firm sufficiently attractive according to the chosen search strategy (i.e. with attractiveness above the 'attractiveness threshold'), it will stop its search and offer a partnership. If the possible partner wishes to return the partnership offer, the partnership is set up.

The model assumes that partners learn only about the knowledge being actively used by the other agent. Thus, to learn from the partner, a firm will add the triples of the partner's innovation hypothesis to its own. It will take care that it will only take triples which are different from its own triples in the innovation hypothesis: the expertise levels of the triples taken from the partner are set down to 1 in order to mirror the difficulty of integrating external knowledge. If the partner has a similar triple in terms of capability and ability but a higher expertise level the firm will drop its own triple in favour of the partner's one; if the expertise level of a similar triple is lower, the firm will stick to its own version. Once the knowledge transfer has been completed, each firm continues to produce its own product, possibly with greater expertise as a result of acquiring skills from its partner.

2.4.4. Networks

If the firm's last innovation was successful, i.e. the amount of its profit in the previous round was above a threshold, and the firm has some partners at hand, it can initiate the formation of a network. This can considerably increase its profits because the network will try to create innovations as an autonomous agent in addition to those

created by its members. It will distribute any rewards to its members who, in the meantime, can continue with their own attempts, thus providing a double chance for profits. However, the formation of networks is costly, which has two consequences: only firms with enough capital can form or join a network and no firm can be member of two networks at the same time.

Networks are "normal" agents, i.e. they get the same amount of initial capital as other firms and can engage in all the activities available to other firms. The kene of a network is the union of the triples from the innovation hypotheses of all its participants. If a network is successful it will distribute any earnings above the amount of the initial capital to its members; if it fails and becomes bankrupt, it will be dissolved.
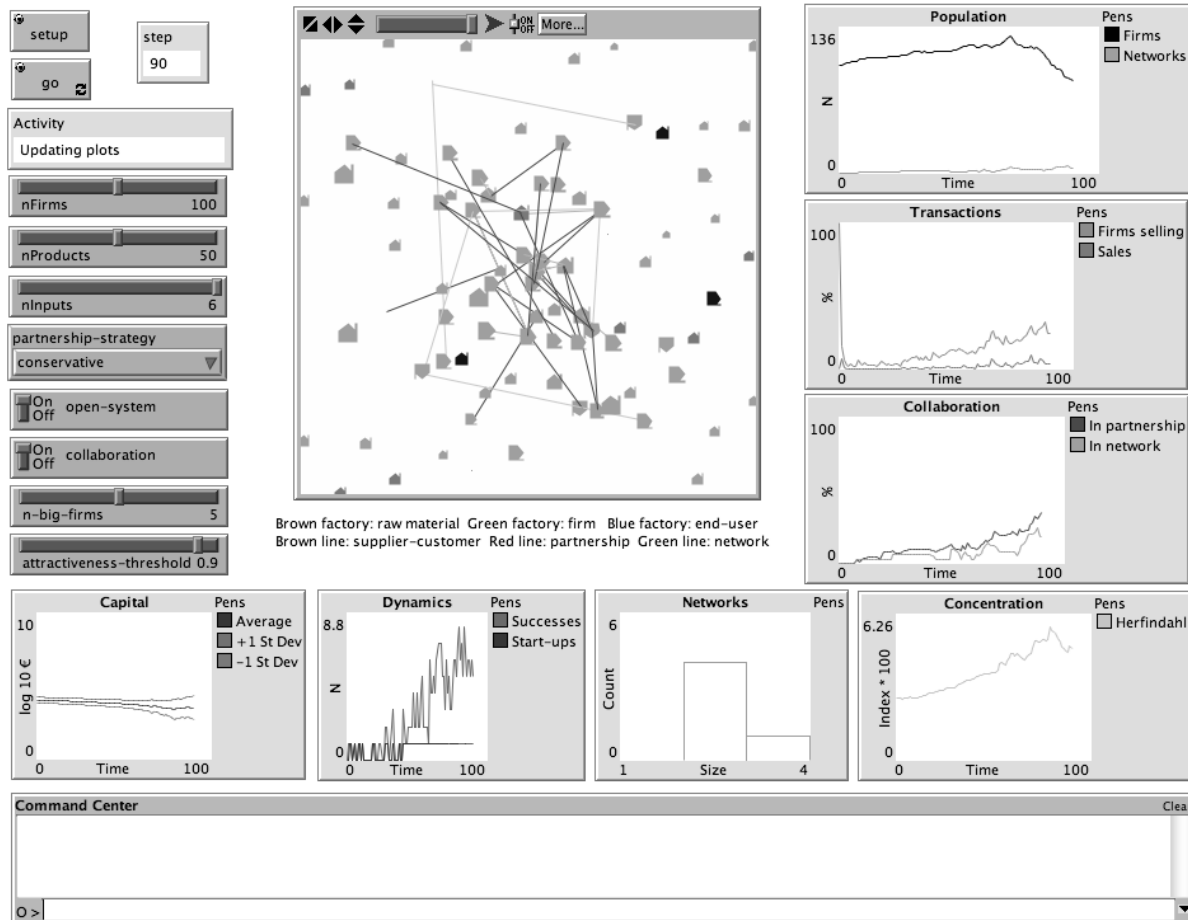
2.5   Start-ups

If the sector is successful, new firms will be attracted into it. This is modelled by adding a new firm to the population when any existing firm makes a substantial profit. The new firm is a clone of the successful firm, but with its kene triples restricted to those in the successful firm's advertisement, and an expertise level of 1. This models a new firm copying the characteristics of those seen to be successful in the market. As with all firms, the kene may also be restricted because the initial capital of a start-up is limited and may not be sufficient to support the copying of the whole of the successful firm's knowledge base.

3. The implementation

The model has been programmed using NetLogo (http://ccl.northwestern.edu/netlogo/) and is available from the authors.

With a complex model such as this one, extensive experiments have to be carried out to understand its behaviour and the sensitivity of the output to variations in the input parameters. This work has not yet been completed. Nevertheless, we can give an impression of how it performs using standard parameter settings.

Figure 5: The interface of the model

Brown factory: raw material Green factory: firm Blue factory: end-user
Brown line: supplier-customer Red line: partnership Green line: network

The main graphic window (Figure 5) shows about 100 firms (represented by the small 'factory' shapes). Their position in the display window is not significant: a layout algorithm is used to move the factory icons to positions where they can best be seen. Factory icons on their side mark firms that were created after the start of the simulation (i.e. they are start ups) and those that are upside down are network firms (firms producing on behalf of a network, with a kene based on the union of the kenes of the network members). The size of the icons indicates the amount of capital its firm possesses (the size is proportional to $\log_{10}$ of the amount of capital).

The numerous lines indicate partnerships, supplier relationships and network linkages between firms. Those not involved in any relationship have been moved by the layout algorithm to the margins of the display. There are 5 networks (one with 4 members and four with 3 members). The networks are shown with lines interconnecting all their members. The medium grey factories are those producing 'raw materials' (these firms require no inputs from within the system in order to create their products); the dark grey ones are 'end-users' that produce no outputs.

The display is surrounded by graphs monitoring various aggregate aspects of the system. At the top right is shown the growth in the population of firms as start-ups are added, and the slow growth in the number of networks. The graph below shows the percentage of firms that have products on the market ('Firms selling') and the percentage that have made a sale ('Sales'); the latter is always less than the former because some firms are unable to find customers prepared to buy at the price proposed for the product. The third graph down the right-hand side indicates the

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percentage of firms that are involved in either at least one partnership or in a network. The bottom right graph shows a measure of the distribution of funds in the market, the Herfindahl concentration index H_t,

$$H_t = \sum_n s_i^t$$

where s_i^t is the relative capital of firm i, which measures the distribution of capital among the firms.

The Networks histogram shows the number of firms in each network, and the Dynamics plot indicates, on the upper Successes graph, the number of firms which have exceeded the threshold of profit that indicates a successful innovation (the 'success threshold') and, on the lower Start Ups graph, the number of new firms entering the market at each round. The Capital plot in the bottom left corner shows the average capital of the firms, expressed as a logarithm base 10.

4. Conclusions

The SKIN model is an attempt to improve our understanding of the complex processes going on in modern innovation. The model goes far beyond previous theoretical attempts in economics of analyzing the industrial organization of innovation processes (e.g. D'Aspremont and Jacquemin, 1988 and all model extensions, see Martin 2003 for an excellent survey). Instead of integrating strategic alliances and cooperative R&D in a standard equilibrium model of oligopolistic competition, insights coming from numerous case and industry studies are used to model the actors' decision procedures relating to innovation processes. Using an agent-based simulation framework allows the modelling of innovation processes through abstracting from reality without assuming away those essential characteristics of innovation processes (e.g. true uncertainty, historical time, heterogeneous agents learning experimentally, the consequences of failure, and learning from each other in partnerships and networks) that are heavily emphasized by modern innovation economists working in an evolutionary framework (e.g. Nelson, 2001).

SKIN allows the investigation of different industries in which there are differing strategies by altering the model's parameters Parameters can be estimated econometrically from data sets describing an industry's cooperative behaviour. Such data sets are becoming increasingly available for e.g. the biotechnology-based industries and the information and telecommunication industries. Alternatively, the historical development of a particular industry can be reproduced by finding a set of parameters that gives a time trace that mirrors the development of the industry. Having reproduced the historical sequence in one industry, one can try to find the critical parameters which change the model's results so that they follow the historical sequence of another industry. With this exercises, which are on our agenda for future research, we will develop a much better understanding of the industries under consideration and will also be able to evaluate different policy measures and their efficacy for particular industries.

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