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RESEARCH PAPER

Avoiding evolutionary inefficiencies in innovation networks

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Innovation policy is in need of a rationale which allows for the design and evaluation of policy instruments. In economic policy, focus has traditionally been placed on market failures, and efficiency measures have been used to decide whether policy should intervene and which instrument should be applied. In innovation policy, this rationale cannot be meaningfully applied because of the uncertain and open character of innovation processes. Uncertainty is not a market failure and cannot be repaired. Inevitably, policy makers are subject to failure and their goals cannot pragmatically be represented by a social optimum. In eschewing the concept of 'optimal innovation', avoiding evolutionary inefficiencies becomes central to analysis and to innovation policy making. Superimposed on the several sources of evolutionary inefficiencies are so-called 'network inefficiencies'. Because of the widespread organization of innovation into innovation networks, network structures and dynamics give useful hints for where and when innovation policy should intervene.

Introduction

Today innovation networks, innovation clusters and innovation systems are an integral part of innovation policies worldwide (EU Commission, 2008; OECD, 2009; Capozzi, 2010). Over the last 20 years, they have enjoyed increasing popularity in practical innovation policies. They provide an outstanding example of the interactive and co-evolutionary process of policy learning and innovation theory (Mytelka and Smith, 2002). However, from a theoretical point of view the effects of innovation networks are still unclear. They would seem to offer opportunities to spur the co-evolutionary process between innovation theory and policy design. The reason for the difficulties in integrating knowledge exchange in networks can be seen in the theoretical body of mainstream economics, which considers innovation as a part of normal economic activities in an optimization framework. Economic policy making requires the evaluation of innovation network policies within the standard efficiency-oriented framework.

Since the 1990s, the idea of innovation systems (IS) has been prominent in modern innovation economics and innovation policy. The proponents of innovation systems emphasize that the neoclassical market failure approach is not relevant for justifying technology policy. Instead, the variety of institutions and actors involved in innovation and the resulting complex interactions among them allow for sufficiently targeted, specific technology policy without referring to market failures in order to justify the non-market parts of the system (Nelson, 2009). This switch from

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the neoclassical to the systemic evolutionary view opens up new possibilities for envisaging policies focussing on innovation and in particular on innovation networks within an alternative framework – one in which innovation is considered in the context of collective learning, experimenting and problem solving.

The innovation systems literature has developed comparative institutional approaches for various levels of abstraction, including national innovation systems (NIS) (Freeman, 1987; Lundvall, 1992; Nelson, 1993), sectoral innovation systems (SIS) (Malerba, 2004) and regional innovation systems (RIS) (Cooke and Morgan, 1998). An important common ingredient of these innovation system approaches is the rejection of the linear view of innovation processes in favour of a systemic view. One example would be the chain-linked model of Kline and Rosenberg (1986), where the functional as well as dysfunctional and bi-directional relations between the various phases of the innovation process and the different actors involved are crucial. The major message of the systemic view is that new knowledge does not spill over automatically to the different actors involved in innovation processes. To understand the knowledge creation and diffusion processes at the national, regional and sectoral levels, one has to understand that the various actors are interlinked in innovation networks.

Most basically, innovation networks consist of actors and linkages among these actors (see Pyka, 2002; Buchmann and Pyka, 2011). Actors are defined very broadly in this context and encompass firms, individuals, research institutes, university laboratories, venture capital firms and standardization agencies. Links among the actors are used as channels for knowledge and information flows, as well as financial flows (as in the case of venture capitalists). The links among actors may be either formal (R&D joint ventures, strategic alliances, research consortia, etc.) or informal, based on personal contacts and recommendations. In essence, innovation networks provide the networking actors with knowledge that might be complementary to their own knowledge, as well as with the other resources necessary to run an enterprise and to survive in innovation competition. Accordingly, innovation networks are a means for the industrial organization of research and development, which is particularly relevant in knowledge-intensive industries with exacting requirements for competent actors, as with rapidly-developing knowledge, the design of interfaces between technologies, and complex innovation. Finally, the operation modes of innovation networks as a means for mutual learning, cross-fertilization and knowledge transfer vary over time. In the early stages of industry development, networks offer platforms for creative exploration of diverse knowledge fields. For mature industries, networks are a tool to exploit efficiently the core competences of specialized agents.

The establishment, manipulation and governance of innovation networks, therefore, are considered appropriate for innovation policy aiming to create dynamic, innovation-driven economic development. How, though, are network-based innovation policies to be designed, varied over time and evaluated? The aim of this paper is to develop a framework which justifies policy interventions from a dynamic, network-based angle. This framework will allow for a rationale for innovation policy in general, and highlight the role of innovation networks in particular. The paper goes on to analyse the efficiency-oriented neoclassical approach. Severe problems arise if innovation processes are considered to be truly uncertain processes. Uncertainty is not ruled out by focussing on innovation networks instead of focussing on the immediate outcome of innovation, as is done in the alternative approach introduced in the following sections. However, this approach is in line with the systemic and evolutionary view, which offers the framework for our central considerations. The paper concludes by identifying the prerequisites of a future-oriented, economic development. These processes are threatened by several evolutionary inefficiencies which displace the idea of an efficient innovation process underlying the neoclassical rationale, and offer a new target for innovation policies. The concept of evolutionary inefficiencies and their avoidance is used to derive guidelines for an innovation policy design focussing on innovation networks.

Repairing market failure – the rationale for innovation policy?

Economic policy in general manipulates structures to provide the prerequisites for an improved allocation of resources in the hope of enabling economic development. Within the mainstream neoclassical framework, a widely accepted benchmark for policy interventions is the so-called 'social optimum', which is achieved in an economic system by a 'benevolent social planner' who considers the individual welfare of all market participants (Arrow, 1951/1963). Because there are rational individuals, market participants automatically realize the welfare optimum in a static setting. With perfect foresight, market participants are also able to realize an inter-temporal welfare optimum because they take into account all future impacts of their economic decisions.

However, for such social optima to be realized, a number of prerequisites must be fulfilled which are not guaranteed and which are responsible for so-called 'market failures'. Therefore, policy interventions are considered as correctives which restore optimal individual incentives for economic decision making in order to achieve the socially optimal outcome. Does this normative policy concept also work in the case of innovation policy? And why is innovation policy an important application of economic policy and therefore subject to economic considerations? To answer the latter question first, technological change and innovation are considered to be the decisive factors determining economic growth (Solow, 1956, 1957). For this reason, at least since the 1950s, economic policy also encompasses innovation processes.

Because of free-rider problems which stem from imperfect appropriability conditions of new technological knowledge, individual incentives to invest in research and development (R&D) are below the socially optimal (Arrow, 1959). In this case, the guideline for innovation policy is to restore individual incentives (for example, by means of R&D subsidies) until the marginal return of R&D equals the marginal costs of R&D. The dynamic goal of innovation policy foresees an economy growing along its equilibrium trajectory and achieving maximum growth through inter-temporal cost-minimization. Transitions from one technology to another (structural change) are smooth processes taking into account, for example, the vintages of production technologies and their requirements for an adjusted depreciation, or adjustment of the educational infrastructure in order to create the human capital required. As in the static case, the installation of new technologies is easily accomplished because of the fully developed competences of market participants. Innovation policy intervenes only when achieving this cost-minimizing path is endangered by, say, sunk costs which make a retreat from obsolete markets difficult (e.g., tax policies), or frictional problems caused by the required shift in human capital (e.g., educational policy).

To design and evaluate innovation policy instruments in this vein, a necessary step is to compare the costs of implementing these policies with the rewards. To this end, several efficiency measures have been applied. In general, these efficiency measures reflect the resources invested in order to achieve a certain outcome. As the outcome is defined by the social welfare optimum, the policy instrument chosen is that which achieves this goal with minimum resources. Innovation policies focussing on the optimal incentives to invest in R&D are evaluated according to a static efficiency concept which relates the costs of policy intervention to the achievement of the optimal incentive level. Various instruments (e.g., R&D subsidies, R&D tax credits, and institutional adjustments such as patents) are then compared and the one with the best cost–benefit ratio is chosen. In a similar way, the dynamic efficiency concept is applied by relating the costs of policy instruments to the goal of following the specified cost-minimizing path.

To summarize, in neoclassical welfare economics, innovation policies are treated just like other kinds of economic policies: given a particular set of assumptions (substantial rationality and equilibrium), market failures are repaired. The task for policy makers is to restore optimal incentives for an efficient allocation of resources from static and dynamic perspectives. Because of well-defined economic decision problems, the choice of policy instruments follows standard efficiency considerations.

From the mid-1970s, the neoclassical framework began to be criticized for being unsuited to the analysis of innovation processes and their impact on economic development. The critics referred to the ideas of Joseph Schumpeter (1912), who conceived innovation as the force which endogenously destroys circular flow (i.e., economic equilibrium). The central point of this criticism focused on the assumption of substantial rationality, which is completely in conflict with the very nature of innovation processes, namely true uncertainty (Knight, 1921). Innovations are characterized by true uncertainty, which cannot be approximated by probability distributions over a known state space. In other words, had an innovation been known *ex ante*, it would not have been an innovation. Instead, the state space itself is unexpectedly modified by its innovative extension. Accordingly, the application of optimization calculus, even in the form of the maximization of expected values, is impossible under such circumstances. Erdmann (1993) coined the notion of the ‘pathological pessimism’ of neoclassical economics with respect to innovation because *homo oeconomicus* would always prefer an extremely small pay-off to a true uncertain pay-off, however large.

Consequently, if true uncertainty is considered to be a fundamental characteristic of innovation, the concept of substantial rationality is misleading and counterfactual as innovation processes would no longer take place. If innovation processes are treated realistically, they can no longer be viewed as optimization processes. This fundamental inability to integrate innovation processes into standard economics has led to the emergence of an understanding of economic development driven by innovation as a cultural evolutionary process (Nelson and Winter, 1982). Innovation processes are now considered to be complex experimental processes with a high probability of failure or, more generally, innovation processes become trial-and-error processes where the learning and acquiring of competences of economic actors are central issues. Instead of substantial rationality, the concept is of a ‘procedural rationality’ (Simon, 1976), which can accommodate learning and imperfect knowledge.

Consequences for innovation policy – the lost benchmark

This consideration of true uncertainty has important implications for innovation policy. Uncertainty is qualitatively very different from market failure, which is so central to neoclassical justification of innovation policies designed to repair market imperfections. Uncertainty is instead a *sine qua non* of innovation processes and cannot be repaired. Indeed, the social planner is also confronted with uncertainty and therefore has incomplete knowledge of future developments and a high probability of failing with his interventions in innovation processes.

For innovation policy, incorporating true uncertainty into the analysis brings with it the painful consequence of losing the convenient benchmark of a social optimum. In the same way, the traditional interpretations of efficiency are no longer applicable to the design and evaluation of innovation policies. Economic evolution in principle is an open process which does not follow an *ex ante* given and well-specified goal. In Dosi's (1988) words: 'Almost by definition, what is searched for cannot be known *ex ante* with any precision before the activity itself … so that the technical (and, even more so, the commercial) outcomes of innovative efforts can hardly be known *ex ante*'. In innovation processes, failure and inefficiencies have to be accepted as the order of the day (Metcalfe, 1994). Of course, in some situations better prerequisites for economic development can be identified than in others. The goals for an innovation policy, then, can only be to identify and support prolific conditions for innovation processes and to avoid bottlenecks for economic development. The epistemological caveat of true uncertainty is always present in every *ex ante* selection. Instead of focussing on well-specified goals, innovation policy has to focus on the innovation process in its own right.

It follows that if economic development driven by innovation is considered an evolutionary process, efficiency concepts are no longer applicable because no well-specified goal can be derived *ex ante*. Furthermore, final decisions are an illusion (Moreau, 2004) and an adaptive policy making perspective is required (Metcalfe and Georghiou, 1997). Consequently, and along much more modest lines, innovation policy has to be designed and evaluated according to the ability to avoid evolutionary inefficiencies whenever possible. As evolutionary inefficiencies we define situations which clearly restrict the potential for future development.

Prerequisites for future-oriented economic development: knowledge generation and diffusion

For sustainable innovation processes, the origin of new knowledge is critical: new knowledge supports the intentional introduction of all kinds of novelty. Therefore, knowledge generation and diffusion processes are at the heart of innovation policy. Essentially, new knowledge originates in two different ways. In the tradition of Adam Smith's (1776) emphasis on the division of labour and specialization, one stream of literature focuses on the need to concentrate on a narrow subset of knowledge in order to excel. In some contrast, modern innovation economics considers learning from diverse knowledge bases to be an equally important source of new knowledge. The re-combination of heterogeneous knowledge bases continuously leads to new knowledge (Simon, 1985). Accordingly, the larger the diverse knowledge pool in an economy, the better the prospects for innovation.

Within modern management theory, this tensioned relationship between the variety of knowledge fields and specialization within single knowledge fields is known as 'exploration *versus* exploitation' (Cyert and March, 1963). Exploration includes the discovery of new techno-economic opportunities, which increases knowledge variety. Exploration involves screening the whole space of opportunities for promising new alternatives. In contrast, exploitation focuses on the advancement in a well-defined technological area. In other words, exploitation deals with the achievement of a high degree of sophistication which can be reached only by specialization.

In isolation, neither knowledge generation mechanism will enable sustainable generation of new knowledge. Exploration alone (i.e., the discovery of new technological opportunities) is not sufficient for economic development; without advancing and excelling in these new technologies, significant economic rewards will not be realized. Exclusively focussing on exploitation (i.e., the mastering and improvement of a new technology) is also not sufficient for a sustainable innovation process as the techno-economic opportunities of a given technology are limited and will sooner or later be exhausted. As a consequence, the innovation process, and economic development with it, will cease (Dosi, 1982; Coombs, 1988).

These firm-level considerations also hold at the level of the whole economy. Saviotti and Pyka (2004) show that increasing productivity in a single technology (an industry) and the emergence of new industries should be seen as complementary for economic development. By increasing productivity in older industries, an economy earns the resources necessary for discovering new techno-economic opportunities, which are necessary for the emergence of new industries. Without the search for new techno-economic opportunities, the economy will stagnate; without increasing the productivity in existing industries, the economy will run short of the resources required in the search for new techno-economic opportunities. From this, it follows that the normative goal of knowledge creation can be specified by goals as 'knowledge variation' or 'specialization'. This means that the targets of innovation policy will vary depending on the specific phase of intervention.

Whether to focus on exploration or exploitation opens up an important dynamic in the evolution of knowledge and economic development (see Gilsing and Nooteboom, 2006). In the course of an industry life-cycle, which activity to focus on will depend on the prevailing situation. In the opening phase of a new industry, innovation-driven entrepreneurial entry is usually combined with exploratory search for promising technological trajectories which will have a positive effect on knowledge variety and the creation of niche markets. In more mature stages of an industry life cycle, however, R&D becomes focused on the exploitation of specific opportunities in order to improve competitiveness. This leads to a decreasing variety of knowledge fields and to a strong accumulation of specialized knowledge. The knowledge base of the industry becomes locked-in to a specific subset of knowledge fields. In this sense, evolution consumes its own fuel as variety decreases with advancement along certain technological trajectories (Metcalfe, 1995). Without a replenishment of the knowledge base through, say, basic research activities and the entrepreneurial implementation of the new knowledge, economic development runs the risk of coming to a halt.

A further obstacle for knowledge evolution and related innovation-driven economic development is the difficulty of diffusing new knowledge among firms. Obviously, in the absence of diffusion of the new knowledge, innovation remains an insular phenomenon without any macroeconomic effects on income per capita, productivity and economic growth. Explanations for the lack of diffusion are to be sought in the exploratory and exploitative phases of knowledge generation. In the exploratory phase, knowledge diffusion might be constrained by malfunctioning knowledge transfer between actors and institutions engaged in basic research and the population of firms. A similar negative effect on the diffusion of new explorative knowledge stems from underdeveloped entrepreneurial activity caused by a lack in venture capital or by an education policy misaligned with the future need of the economy to expand into new fields (Hanusch and Pyka, 2007).

In addition, in the exploitative phase of knowledge generation, diffusion can be strongly inhibited by missing links among the firms in an industry. Today's technological solutions are often complex, which means a large variety of knowledge fields are likely to be relevant to a new technology. Teece (1988) coined the notion of 'combinatorial innovation' in this context, meaning that hardly any firm is able to master all the technological areas relevant to a new technology, and to develop further relevant knowledge fields. In the absence of a dense network of linkages with other actors engaged in the innovation process, knowledge cannot diffuse widely and rapidly.

To summarize, the following four issues are identified as necessary conditions for innovation-driven economic development: (i) exploration of new techno-economic opportunities in order to increase the variety of knowledge fields; (ii) exploitation of techno-economic opportunities to realize the economic benefits of innovation processes; and (iii) mastery of the dynamic trade-off between exploration and exploitation activities in order to provide a rich variety of knowledge assets in the long run and simultaneously to excel in a small subset of knowledge fields in the short run. From a dynamic perspective, the economic system has to balance an adequate mix of explorative activities where new techno-economic opportunities are discovered, and exploitative activities foster economic growth and income development. Issue (iv) concerns the knowledge generation and diffusion processes; for these to work adequately and to realize beneficial effects for an economy, the relevant actors need to be interlinked so that knowledge can travel among the various agents and the various phases of the innovation process.

Evolutionary inefficiencies

Each of these four prerequisites is in danger of not being fulfilled, which jeopardizes the prospects of innovation-driven economic development. Accordingly, four different sources of evolutionary inefficiencies can be derived: (i) exploration inefficiencies; (ii) exploitation inefficiencies; (iii) balance inefficiencies; and (iv) network inefficiencies.

(i) A situation where exploration inefficiencies hinder economic development can be detected when the prevailing research orientation in an economy is biased towards application. Sooner or later, the specific opportunities of a certain technology will be depleted and technological progress will slow. Improvements become increasingly expensive because of the absence of opportunities which arise from cross-fertilization with other technologies (Coombs, 1988). A similar negative effect for economic development can be traced back to an underdeveloped propensity to found new companies in the economy, or to administrative hurdles hindering entrepreneurial activities. Without start-up companies which use new knowledge for innovation, the transfer of knowledge from basic to applied research is considerably hindered.

(ii) While exploration inefficiencies can be found in situations where the economic actors are nonetheless intensively engaged in R&D, exploitation inefficiencies are caused by insufficient research intensity. A firm's inadequate research activity can be traced back either to ignorance of the innovation of competing firms (e.g. the not invented here syndrome) (Katz and Allen, 1982), or to missing absorptive capacities (Cohen and Levinthal, 1989). Yet another explanation might be a shortage of adequate competences in the labour force, which restricts access to new technologies. An insufficient level of R&D along with a mismatch in the competencies available, lead to an accumulation of relevant knowledge in new industries that is too slow to trigger the innovation dynamics necessary to survive in the global competition.

(iii) Although the rapid accumulation of knowledge is a prerequisite for the development of new industries, it may not be compatible with long-run development. Concentration on a particular subset of knowledge that is too early may exclude promising alternative fields of knowledge and might lead to lock-in effects which drastically reduce the possibilities of development. Consequently, not all promising alternatives are followed up and significant techno-economic opportunities remain unexplored. These balance inefficiencies stem from a patchy mixture of exploration and exploitation activities which can lead to rejection of promising new knowledge. Simultaneously, the economic actors do not discard exhausted techno-economic opportunities in time and carry on with previously successful technologies for too long (Eliasson, 1991). On the other hand, balance inefficiencies might also be caused by an overly high degree of variety in competing knowledge fields when a new industry has to move into the exploitation stage. Without the development of a dominant design to facilitate complementarities in different technologies and industrial norms (Abernathy and Utterback, 1975), new industries run into trouble in their early stages. If new technologies cannot diffuse rapidly and widely, they cannot be expected to have much economic impact.

(iv) Finally, network inefficiencies stem from missing and/or malfunctioning links among economic actors participating in innovation processes. Network inefficiencies (in the sense of missing links among actors) hamper the diffusion of new knowledge and hinder the discovery of cross-fertilization opportunities among seemingly disconnected knowledge fields. However, it is not only missing links that cause network inefficiencies. They can also be caused by networks which are too large (implying high coordination costs), by an imbalance of linkages among actors, which opens up possibilities for strategic control of knowledge flows within innovation networks as with gatekeepers and structural holes (Burt, 1992; Ahuja, 2000), or by decreasing network dynamics which exclude actors with dissimilar knowledge. In these cases, it is not only the existence of linkages among actors that is relevant for innovation policy, but also their distribution and their qualitative features. Network inefficiencies should be considered a general concept which is superimposed on other inefficiency concepts. Because of the complex nature of modern innovation processes, the knowledge required for successful innovation is dispersed and the relevant actors have to exchange and combine the knowledge in networks in order to innovate. Innovation processes organized in innovation networks, therefore, shift the attention of innovation policy to network inefficiencies.

It is possible that a basic research orientation may be missing among economic actors. This could be responsible not only for exhausted economic growth potentials, but also for missing links among universities and other basic and applied research-oriented institutions (Ahrweiler *et al.*, 2011). Without suitable network structures to connect these different groups of actors, the necessary knowledge transfers fail to take place. New achievements in basic research literally stay disconnected and never reach the applied dimension, with strong negative effects on innovation. However, strong and encompassing innovation networks might cause exploitation inefficiencies. This is the case of malfunctioning network ties which hinder the discovery of novelty and the creation of new techno-economic niches. The organization of industrial R&D in innovation networks runs the danger of a knowledge selection within the innovation network which repeats the not invented here syndrome at the network level.

It follows that network inefficiencies can appear together and aggravate the balance inefficiencies by encouraging the emergence of lock-in effects, thereby excluding promising alternatives too early. In cases where the entry into innovation networks is blocked or potential members are excluded because of assumed incompatibility of their knowledge base, the knowledge of the members of the innovation network increasingly aligns and makes novel combinations within the innovation network less likely. However, if the balance inefficiencies are caused by missing norms and standards, the negative effects on industrial evolution are aggravated by missing links among actors. As innovation networks offer the channels for communication and knowledge transfer, they are considered to be the ideal organizational form for the development of the common standards and norms necessary to spur industrial development in the transition between the explorative and the exploitive phase of industrial evolution.

The evolutionary inefficiencies discussed in this section threaten economic development (Pelikan, 2003). Economic development might be blocked by lock-in into inferior technologies (exploration inefficiencies). Also, excessively wasteful developments caused by the inability of the economic system to trigger sufficient industrial dynamics might restrict prolific economic development (exploitation inefficiencies). Finally, economic development can become misdirected because of imbalance between exploration and exploitation orientation. Because of the prominent role innovation networks play in complex innovation processes, network inefficiencies are clearly superimposed on these evolutionary inefficiencies and offer a promising starting point for innovation policy.

Innovation policy and innovation networks

The consideration of true uncertainty in innovation processes necessarily implies the loss of a benchmark which might have offered a point of reference for the design of innovation policies. What remains instead of goal-orientation for innovation policy is process-orientation; that is, taking care of conditions for innovation-driven economic development. This process-oriented view, which is in line with the systemic and evolutionary approaches in innovation economics, suggests a rationale for innovation policy which focuses on the avoidance of bottlenecks in economic development (i.e., evolutionary inefficiencies).

As uncertainty in innovation is ubiquitous, policy makers cannot escape it and therefore permanently run the risk of failure in their attempts to manipulate innovation processes. In the more realistic framework of evolutionary economics, the success of policy intervention is truly uncertain (Moreau, 2004). Focussing on well-specified, technological goals in mission-oriented policy design inevitably provokes misdirected developments (Ergas, 1987; Cantner and Pyka, 2001). Although failure *per se* cannot be excluded, the risk of wasting public money is considerably smaller when the focus of innovation policy is on knowledge generation and diffusion.

In the efforts to govern innovation processes, useful hints for the design of innovation policies can be found in the structures and dynamics of underlying innovation networks. The complex and combinatorial nature of innovation puts innovation networks at the very centre of innovation policy: first, innovation networks are a widespread organizational form for innovation processes, and second, network inefficiencies are superimposed on other evolutionary efficiencies and can therefore be considered as the entrance point for endeavours to manipulate innovation processes.

In general, innovation networks offer a flexible environment for innovation processes by horizontally and vertically interlinking the involved actors. The linkages in the networks can be considered as channels for knowledge transfer that are essential in complex innovation processes where different fields of knowledge are relevant and the actors are specialized in a small subset of knowledge fields only, namely their core competencies. Vertically, innovation networks connect the different steps in the value chains (resource industries, investment good industries, producers and customers), as well as the different phases of innovation processes. In innovation networks, the actors within industries are horizontally connected to exchange knowledge, learn together, develop standards and norms, and advance underlying technologies. From a dynamic perspective, innovation networks change their character from informal to more formal forms of cooperation over an industry life cycle (Pyka, 2000). Although one might expect these innovation networks to emerge and to develop in a self-organizing way, obstacles to their emergence, misguided developments and malfunctioning links cannot be ruled out (e.g., Pyka and Windrum, 2003).

This is where network inefficiencies enter as a target for policy intervention. The creation, the growth and the closure of innovation networks can be influenced by innovation policy instruments. Policy can offer incentives to enter R&D collaborations, which then serve as kernels for network evolution. Also, policy programmes can be implemented which focus on knowledge transfer between basic and applied research by strengthening university–industry linkages. Public actors themselves can enter innovation networks and play important roles as network facilitators and network triggers by inviting other actors to join the innovation network, by increasing the coverage of different knowledge fields, and by taking over important coordination tasks. Furthermore, policy can generate environments which support the emergence of informal networks in particular in the very early phases of the evolution of new technologies.

Obviously, advocating that innovation policies should be concerned with only the creation of innovation networks and the strengthening of linkages among actors within an economy would be an insufficient guidance in the struggle with evolutionary inefficiencies. Innovation networks are complex organizational forms whose structures are subject to significant changes over time. Structures which are beneficial in exploratory phases might turn out to be obstacles in the exploitative stages of the innovation process (and *vice versa*). In the literature, indicators from graph theory and social network analysis have been discussed. These include the centrality of actors in networks, the average path length among actors, and the density of networks. They describe particular occurrences of network structures and their meaning for the functioning of innovation networks (see Buchmann and Pyka, 2011).

An example will help to illustrate these network dynamics: Saviotti and Catherine (2008), for instance, analyze innovation networks in the biopharmaceutical industries and find characteristic patterns in density and centrality. The strong innovative performance of these industries suggests these might be considered to be examples for other knowledge-intensive industries. In the early exploratory phases of the industries, the observed networks are characterized by decreasing density. The networks are joined by a growing number of firms, which bring in their specialized knowledge, thereby increasing the variety of knowledge fields accessible in the network for exploration activities. The linkages in this growing innovation network, however, are not frequent and therefore its density decreases (see Figure 1). In exploitative stages, when the knowledge base in the innovation network has already matured, the network stops growing and the linkages among actors become much more frequent (i.e., the density of the network increases again). This increasing density indicates strong knowledge transfer among actors in order to increase the efficiency of an innovation process along a well-defined technological trajectory in the exploitative stage.

In a similar vein, the centrality in the network, an indicator which measures the distribution of linkages among actors, varies systematically (see Figure 2). In early explorative stages, centrality measures are small, indicating a more or less equal distribution of network activities. In later stages, however, the centrality increases and the innovation networks even show some scale-free attributes (Barabasi and Albert, 1999). The reason for this change is to be seen in the two different populations of firms which basically create the innovation networks in biopharmaceuticals, namely small start-up companies specialized in a small subset of biotechnology competences, and large pharmaceutical companies with vast and diversified knowledge bases. The large pharmaceutical companies entertain a lot of cooperative

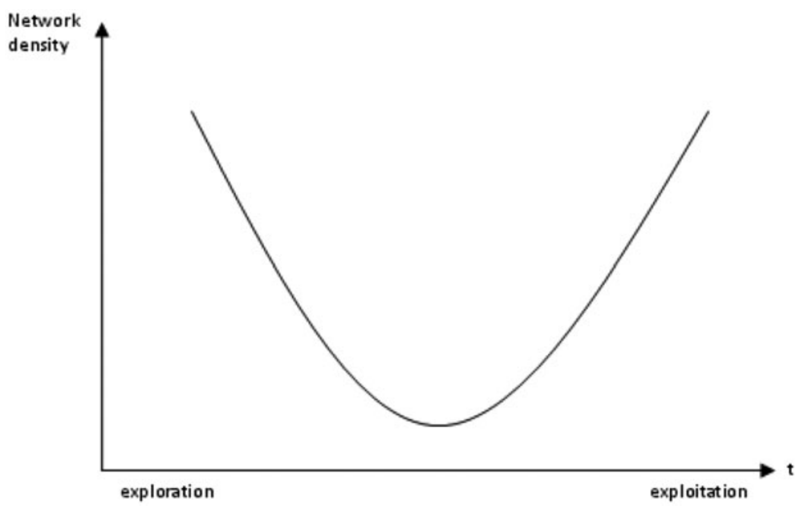

Figure 1. Decreasing and increasing network densities in the industry life cycle

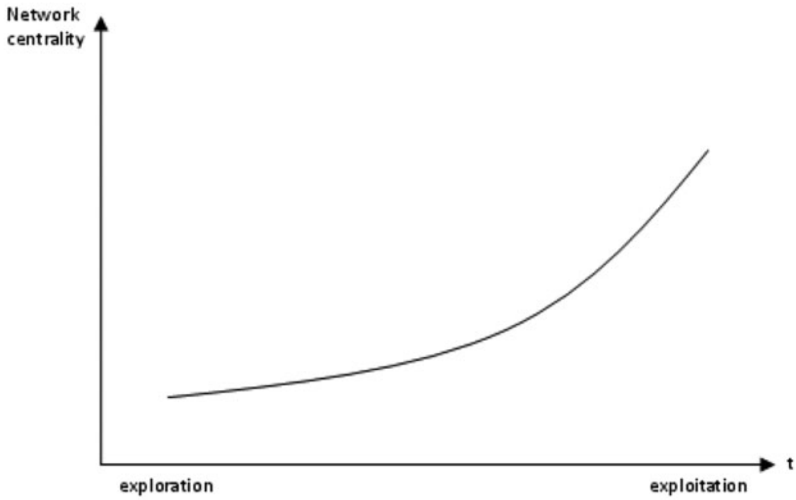

Figure 2. Increasing network centralities in the industry life cycle

relationships with small companies in the exploitation stage, whereas each small company generally has only a small number of linkages in the network. In the early explorative stages of the industry's life cycles, such differences do not appear.

The example illustrates that the structures and dynamics of innovation networks are characterized by specific patterns which are observable through a number of indicators. From a process-oriented perspective, innovation policy can determine from these indicators and their development during the life-cycle of an industry whether and how to intervene in order to avoid potential network inefficiencies. In the early explorative stages of a technology, technological variety can be considered more important than dense relationships within the innovation network. If the entry rate in the network starts to decrease, innovation policy is asked to intervene and to create conditions which allow for a broadening of the underlying knowledge base. Similarly, in exploitation stages a stagnant network density might indicate that the industry has difficulties in developing a dominant design. In this case, innovation policies focussing on increasing relationships within the network will support the creation of common standards and norms and thereby emphasize and accelerate industry evolution. In the first case, innovation policy can avoid exploration inefficiencies by taking care of network inefficiencies. It can also balance inefficiencies which might stem from early lock-in into a particular technology or by a not invented in the network phenomenon. In the latter case, exploitation inefficiencies are avoided by smoothing out network inefficiencies.

Because of unavoidable uncertainty in innovation processes, failure cannot be excluded – it accompanies firms as well as policy actors. In particular, identifying the passage from exploration to exploitation activities causes severe difficulties, and unique patterns in the evolution of the innovation networks are not to be expected. Nevertheless, by focussing on innovation processes instead of well-specified innovative outcomes, and by observing the development of the underlying innovation network structures, potential evolutionary inefficiencies are identified in time to respond to corrective steering of appropriate innovation policy.

Conclusions

In practical innovation policy, increasing focus on innovation networks cannot be neglected. Although popular in application, the rationale for innovation networks as well as their evaluation is not clear from a theoretical perspective. We argue that the focus on market failure is not applicable in innovation policy because of the inevitable uncertainty of innovation processes. Therefore, innovation policy has to apply a much more modest rationale which abandons the possibility of optimal solutions and instead attempts to avoid situations which hamper economic development.

Because of the outstanding importance of innovation networks in the organization of R&D processes, they offer a promising starting point for a process-oriented innovation policy. Network inefficiencies are superimposed on other evolutionary inefficiencies and are therefore a primary target for innovation policy. From this perspective, the structures and dynamics of innovation networks become the focus of attention as well as the starting point of action in innovation policy.

Obviously, such an innovation policy requires substantial information about innovation networks, their architectures and their dynamics. So far, only limited knowledge of specific patterns of innovation network dynamics is available. Furthermore, unique patterns which can readily be drawn upon to dictate suitable innovation policy cannot be expected because of sectoral and technological specificities. The future research agenda needs to emphasize empirical investigation of innovation networks, to create new databases on innovation networks, and to improve indicators for the analysis of complex innovation networks. A promising approach to improve our knowledge about innovation network dynamics and their changing compositions is offered by agent-based models. These can be used as policy laboratories in order to evaluate *ex ante* the impact of policy instruments on network structures. Ahrweiler *et al.* (2014) reproduce the networks of the so-called 'European research landscape' generated by the framework programmes of the European Commission. This simulation environment is then used to test *in silico* the potential outcome of various policy instruments in the Horizon 2020 framework (e.g., concerning the underlying network architectures and the participation rate of SMEs). These new simulation tools will allow the closing of information gaps on innovation networks in the near future. As Mytelka and Smith (2002) note, there is huge potential in the co-evolution of policy learning and innovation theory.

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References

Abernathy, W. and Utterback, J. (1975) 'A dynamic model of process and product innovation', *Omega*, 3, 6, pp.639–56.

Ahrweiler, P., Gilbert, N. and Pyka, A. (2011) 'A new model for university–industry links in knowledge-based economies', *Journal of Product Innovation Management*, 28, pp.218–35.

Ahrweiler, P., Schilperoord, M., Pyka, A. and Gilbert, N. (2014) 'Testing policy options for Horizon 2020 with SKIN' in Ahrweiler, P., Gilbert, N. and Pyka, A. (eds) *Simulating Knowledge Dynamics in Innovation Networks*, *Understanding Complex Systems*, Springer, Berlin, pp.155–84.

Ahuja, G. (2000) 'Collaboration networks, structural holes, and innovation: a longitudinal study', *Administrative Science Quarterly*, 45, pp.425–55.

Arrow, K. (1951/1963) *Social Choice and Individual Values*, Yale University Press, New Haven CT.

Arrow, K. (1959) *The Rate and Direction of Inventive Activity, Economic Welfare and the Allocation of Resources for Invention,* Economics Division P-1856, Rand Corporation, Santa Monica CA.

Barabasi, A. and Albert, R. (1999) 'Emergence of scaling in random networks', *Science*, 286, 5439, pp.509–12.

Buchmann, T. and Pyka, A. (2011) 'Innovation networks' in Krafft, J. and Dietrich, M. (eds) *Handbook on the Theory of Firms*, Edward Elgar, Cheltenham, pp.466–84.

Burt, R. (1992) *Structural Holes*, University of Chicago Press, Chicago.

Cantner, U. and Pyka, A. (2001) 'Classifying technology policy from an evolutionary perspective', *Research Policy*, 30, pp.759–75.

Capozzi, M. (2010) 'Leadership and innovation', *Development Outreach*, 21, 1, pp.25–8.

Cohen, W. and Levinthal, D. (1989) 'Innovation and learning: the two faces of R&D', *Economic Journal*, 99, pp.569–96.

Cooke, P. and Morgan, K. (1998) *The Associational Economy: Firms*, Oxford University Press, Oxford.

Coombs, R. (1988) 'Technological opportunities and industrial organization' in Dosi, G. *et al.* (eds) *Technical Change and Economic Theory*, Pinter, London, pp.295–308.

Cyert, R. and March, J. (1963) *A Behavioural Theory of the Firm*, Prentice Hall, Englewood Cliffs NJ.

Dosi, G. (1982) 'Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technological change', *Research Policy*, 11, pp.147–62.

Dosi, G. (1988) 'The nature of the innovative process' in Dosi, G. *et al.* (eds) *Technical Change and Economic Theory*, Pinter, London, pp.221–38.

Eliasson, G. (1991) 'Deregulation, innovative entry and structural diversity as a source of stable and rapid economic growth', *Journal of Evolutionary Economics*, 1, pp.49–63.

Erdmann, G. (1993) *Elemente Einer Evolutorischen Innovationstheorie*, J.C.B. Mohr, Tübingen.

Ergas, H. (1987) 'The importance of technology policy' in Dasgupta, P. and Stoneman, P. (eds) *Economic Policy and Technological Performance*, Cambridge University Press, Cambridge.

EU Commission (2008) *The Concept of Clusters and Cluster Policies and their Role for Competitiveness and Innovation: Main Statistical Results and Lessons Learned*, INNOVA/PRO INNO paper 9, Brussels.

Freeman, C. (1987) *Technology and Economic Performance: Lessons from Japan*, Pinter, London.

Gilsing, V. and Nooteboom, B. (2006) 'Exploration and exploitation in biotechnology industries: the case of pharmaceutical biotechnology', *Research Policy*, 35, pp.1–26.

Hanusch, H. and Pyka, A. (2007) 'Principles of neo-Schumpeterian economics', *Cambridge Journal of Economics*, 31, pp.275–89.

Katz, R. and Allen, T. (1982) 'Investigating the not invented here (NIH) syndrome: a look at the performance, tenure and communication patterns of 50 R&D project groups', *R&D Management*, 12, pp.7–19.

Kline, S. and Rosenberg, N. (1986) 'An overview of innovation' in Landau, R. and Rosenberg, N. (eds) *The Positive Sum Strategy: Harnessing Technology for Economic Growth*, National Academic Press, Washington DC, pp.275–305.

Knight, F. (1921) *Risk, Uncertainty and Profit*, Hart, Schaffner and Marx Prize Essay 31, Houghton Mifflin, Boston.
Lundvall, B. (ed.) (1992) *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning*, Pinter, London.
Malerba, F. (2004) *Sectoral Systems of Innovation*, Cambridge University Press, Cambridge.
Metcalfe, S. (1994) 'Evolutionary economics and technology policy', *Economic Journal*, 104, pp.931–44.
Metcalfe, S. (1995) 'Technology systems and technological policy in an evolutionary framework', *Cambridge Journal of Economics*, 19, pp.25–46.
Metcalfe, S. and Georghiou, L. (1997) *Equilibrium and Evolutionary Foundations of Technology Policy*, Discussion Paper 3, Centre for Research on Innovation and Competition, University of Manchester.
Moreau, F. (2004) 'The role of the state in evolutionary economics', *Cambridge Journal of Economics*, 28, pp.847–74.
Mytelka, L. and Smith, K. (2002) 'Policy learning and innovation theory: an interactive and co-evolving process', *Research Policy*, 31, pp.1467–79.
Nelson, R. (ed.) (1993) *National Systems of Innovation*, Oxford University Press, Oxford.
Nelson, R. (2009) 'Building effective innovation systems versus dealing with market failures as ways of thinking about technology policy' in Foray, D. (ed.) *The New Economics of Technology Policy*, Edward Elgar, Cheltenham, pp.7–17.
Nelson, R. and Winter, S. (1982) *An Evolutionary Theory of Economic Change*, Belknap, Cambridge MA.
OECD (2009) *Open Innovation in Global Networks*, OECD, Paris.
Pelikan, P. (2003) 'Why economic policies need comprehensive evolutionary analysis' in Pelikan, P. and Wegner, G. (eds) *The Evolutionary Analysis of Economic Policy*, Edward Elgar, Cheltenham, pp.15–45.
Pyka, A. (2000) 'Informal networking and industrial life cycles', *Technovation*, 20, pp.25–35.
Pyka, A. (2002) 'Innovation networks in economics – from the incentive-based to the knowledge-based approaches', *European Journal of Innovation Management*, 5, 3, pp.152–63.
Pyka, A. and Windrum, P. (2003) 'The self-organization of strategic alliances', *Economics of Innovation and New Technology*, 12, pp.245–68.
Saviotti, P. and Catherine, D. (2008) 'Innovation networks in biotechnology' in Patzelt, H. Brenner, T. and Audretsch, D. (eds) *Handbook of Bioentrepreneurship,* Springer, Berlin, pp.51–80.
Saviotti, P. and Pyka, A. (2004) 'Economic development by the creation of new sectors', *Journal of Evolutionary Economics*, 14, 1, pp.1–36.
Schumpeter, J. (1912) *Theorie der wirtschaftlichen entwicklung*, Duncker & Humblot, Berlin.
Simon, H. (1976) 'From substantial to procedural rationality' in Latsis, S. (ed.) *Method and Appraisal in Economics*, Cambridge University Press, Cambridge, pp.129–48.
Simon, H. (1985) 'What we know about the creative process' in Kuhn, R. (ed.) *Frontiers in Creative and Innovative Management*, Ballinger, Cambridge MA, pp.3–22.
Smith, A. (1776) *The Wealth of Nations*, Penguin Classics [reprinted 1986].
Solow, R. (1956) 'A contribution to the theory of economic growth', *Quarterly Journal of Economics*, 70, 1, pp.65–94.
Solow, R. (1957) 'Technical change and the aggregate production function', *Review of Economics and Statistics*, 39, 3, pp.312–20.
Teece, D. (1988) 'Technological change and the nature of the firm' in Dosi, G. *et al.* (eds) *Technical Change and Economic Theory*, Pinter, London, pp.263–81.