Innovation systems: analytical and methodological issues [☆]

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Abstract

Innovation systems can be defined in a variety of ways: they can be national, regional, sectoral, or technological. They all involve the creation, diffusion, and use of knowledge. Systems consist of components, relationships among these, and their characteristics or attributes.

The focus of this paper is on the analytical and methodological issues arising from various system concepts. There are three issues that stand out as problematic. First, what is the appropriate level of analysis for the purpose at hand? It matters, for example, whether we are interested in a certain technology, product, set of related products, a competence bloc, a particular cluster of activities or firms, or the science and technology base generally—and for what geographic area, as well as for what time period. The choice of components and system boundaries depends on this, as does the type of interaction among components to be analyzed. The attributes or features of the system components that come into focus also depend on the choice of level of analysis.

The second and closely related issue is how to determine the population, i.e. delineate the system and identify the actors and/or components. What are the key relationships that need to be captured so that the important interaction takes place within the system rather than outside?

The third issue is how to measure the performance of the system. What is to be measured, and how can performance be measured at the system level rather than at component level? © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The systems approach to the analysis of economic and technological change is not new. Several systems approaches have been suggested in the literature. A system may be defined as "a set or arrangement of things so related or connected as to form a unity or organic whole" (Webster's Collegiate Dictionary). Given that different systems serve different purposes,

it is not surprising that there exists a variety of systems concepts. The object of this paper is to review some of the most important analytical and methodological issues which arise in applying a systems approach to the analysis of technological innovation.

Systems of innovation can be viewed in several dimensions. One important dimension is the physical or geographical dimension. Sometimes the focus is on a particular country or region which then determines the geographic boundaries of the system. In other cases the main dimension of interest is a sector or technology. In such cases, the determination of the relevant geographic boundaries is itself a theoretical or at least methodological issue. Due to the vast improvements in communication technology in recent

decades, there is an international dimension to almost any economic activity. How to delineate a system is therefore an important issue.

Another dimension is that of time. In a system with built-in feedback mechanisms, the configuration of components, attributes, and relationships is constantly changing. Thus, a snapshot of the system at a particular point in time may differ substantially from another snapshot of the same system at a different time.

In the literature on systems of innovation there has not been much explicit discussion of the function or purpose of each system, nor of what constitutes inputs and outputs of the system. As a result, there is not much discussion of system performance either. Certainly, it is of great interest to measure or at least assess performance when similar systems are compared. Thus, the measurement of system performance raises another set of issues.

The paper is organized as follows. In the next section, we define what we mean by a 'system'. We then review a variety of concepts of innovation systems which have appeared in the literature. This is followed by a discussion of common methodological issues arising in the empirical application of the system of innovation concept. We conclude with a brief summary of the main findings.

2. What is a system?

Systems engineers define a system as a set of interrelated components working toward a common objective. *Systems are made up of components, relationships, and attributes.*

Components are the operating parts of a system. They can be of a variety of types: actors or organizations such as individuals, business firms, banks, universities, research institutes, and public policy agencies (or parts or groups of each). They can be physical or technological artifacts such as turbogenerators, transformers, and transmission lines in electrical power systems and biomedical devices, diagnostic techniques, and drugs in biomedical/biotechnological systems. They can also be institutions in the form of legislative artifacts such as regulatory laws, traditions, and social norms.

Relationships are the links between the components. The properties and behavior of each component of the set influence the properties and behavior of the set as a whole. At the same time, each component depends upon the properties and behavior of at least one other component in the set. Because of this interdependence, the components cannot be divided into independent subsets; the system is more than the sum of its parts (Blanchard and Fabrycky, 1990, p. 2). Also, if a component is removed from a system or if its characteristics change, the other artifacts in the system will alter characteristics accordingly (Hughes, 1987, p. 51), and the relationships among them may also change—provided that the system is robust. A non-robust system would simply collapse if an essential component were removed. Thus, a function (say venture capital finance) which is carried out by a particular set of actors in specific forms may be carried out by another set of actors and under different arrangements in a similar system at a different time or in a different place.

Relationships involve market as well as non-market links. Feedback (interaction) is what makes systems dynamic; without such feedback, the system is static. Put differently, the greater the interaction among the components of a system, the more dynamic it is. But even a highly dynamic system may not be able to survive, unless it evolves in the right direction.

One of the most important types of relationships in innovation systems involves technology transfer or acquisition, some of which takes place via markets, some via non-market interaction. Indeed, one could argue that technology transfer is the core activity in an innovation system. Some technology may be transferred unintentionally or accidentally; in such cases the term "technological spillovers" may be appropriate. In other cases the technology transfer is clearly intentional for both supplier and receiver. But in neither case can it happen without considerable investment in time and effort by the recipient to attain the required receiver competence. Technology acquisition usually involves a collaborative process of some duration, not a once-for-all transaction.

One result of interaction (feedback) among actors is that capabilities shift and grow over time, and therefore, the system configuration also changes.

Attributes are the properties of the components and the relationships between them; they characterize the system. "Because the components of a technological system interact, their characteristics derive from the system" (Hughes, 1987, p. 52). In other words,

the features which are crucial for understanding the system are related to the function or purpose served by the system, as well as the dimensions in which it is analyzed. The function of an innovation system is to generate, diffuse, and utilize technology. Thus, the main features of the system are the capabilities (together representing economic competence) of the actors to generate, diffuse, and utilize technologies (physical artifacts as well as technical know-how) that have economic value.

Economic (or techno-economic) competence is defined as the ability to identify and exploit business opportunities (Carlsson and Eliasson, 1994). This involves four types of capability. The first is *selective (or strategic) capability*: the ability to make innovative choices of markets, products, technologies, and organizational structure; to engage in entrepreneurial activity; and to select key personnel and acquire key resources, including new competence. The key question here is one of effectiveness: are we doing the right thing? Too often this capability is simply assumed in the economic literature to exist and to be evenly distributed across firms—clearly contrary to what we observe. An important part of this capability is the notion of receiver competence or absorptive capacity: the ability to scan and monitor relevant technological and economic information, to identify technical and market opportunities, and to acquire knowledge, information, and skills needed to develop technologies.

The second element of economic or techno-economic competence is *organizational (integrative or coordinating) ability*. This is the main function of middle management in an organization: to organize and coordinate the resources and economic activities within the organization so that the overall objectives are met. This includes the ability to generate and improve technologies through new combinations of existing knowledge and skills.

The third element is technical or *functional ability*. It involves the efficient execution of various functions within the system to implement technologies and utilize them effectively in the market. The key question here is that of efficiency: are we doing things right?

The fourth element is the *learning (or adaptive) ability*, the ability to learn from success as well as failure, to identify and correct mistakes, to read and interpret market signals and take appropriate actions, and

to diffuse technology throughout the system.[1] This ability is essential for long-term survival. A firm which is both effective and efficient at a point in time eventually becomes neither, unless it can adapt to changing circumstances (especially changing technology).

The dynamic properties of the system—robustness, flexibility, ability to generate change and respond to changes in the environment—are among its most important attributes. Change can be generated endogenously: new components (actors, technological artifacts) are introduced while others exit; the relationships among the components change; and the attributes (capabilities of actors, nature and intensity of links among actors) change. Similar changes can be induced or necessitated by changes in the environment, e.g. the changes in the nature and frequency of interaction among entities made possible through the Internet.

3. Various systems approaches

One of the earliest system concepts used in the literature is that of *input/output analysis* (Leontief, 1941), focusing on the flows of goods and services among sectors in the economy at a particular point in time. Here, it is clear what the inputs and outputs are and how the system is configured. The components and relationships in the system are viewed at the meso (industry) level. The links among the components of the system are basically one-way, i.e. the system is static.

Another early approach is that represented by '*development blocs*' as defined by Dahmén (1950): sequences of complementarities which by way of a series of structural tensions, i.e. disequilibria, may result in a balanced situation (Dahmén, 1989, p. 111). The basic idea is that as an innovation creates new opportunities, these opportunities may not be realized (converted into economic activity) until the pre-requisite inputs (resources and skills) and product markets are in place. Each innovation, therefore, gives rise to a 'structural tension' which, when resolved, makes progress possible and may create new tensions and which, if unresolved, may bring the process to

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[1] Chang (1999) uses a similar terminology at the system level, distinguishing between absorptive, combinative, implementation, and endogenizing capabilities.

a halt. Thus, while the input/output analysis is static, Dahmén's concept already is dynamic, representing one of the first attempts to apply Schumpeterian analysis. It incorporates the notion of disequilibrium and focuses on the role of the entrepreneur. The output of the system not only grows over time but also changes in character and content. Dahmén's analysis focuses on the inter-war period (1919–1939), not just a single year, and it is highly disaggregated, covering the structural development of 24 different industries in Sweden.

A third but much later approach is widely known as *national innovation systems* (Freeman, 1988; Lundvall, 1988, 1992; Nelson, 1988, 1993; and subsequently many others). Here, the framework is broadened beyond the input/output system to include not only industries and firms, but also other actors and organizations, primarily in science and technology, as well as the role of technology policy. The analysis is carried out at the national level: R&D activities and the role played by universities, research institutes, government agencies, and government policies are viewed as components of a single national system, and the linkages among these are viewed at the aggregate level. Because of the size and complexity of the system (and therefore, the large number of linkages among components at lower levels of aggregation), the empirical emphasis in the studies carried out thus far is mainly on statics or comparative statics. But there is nothing in principle preventing a more dynamic analysis.

Another approach is represented by Michael Porter's '*diamond*', described in his 1990 book (*The Competitive Advantage of Nations*). The four sides of the diamond are made up of factor conditions (skills, technologies, capital, etc.), demand conditions (especially "competent demand" as represented, e.g. by technically sophisticated customers), links to related and supporting industries, and firm strategies, structure, and rivalry. Each economic activity is viewed primarily as an industry, but is also as part of a cluster of activities and agents rather than as taking place in isolation. Because of the industry focus, Porter strongly emphasizes the role of competition among actors within industries (i.e. market competition) while suppressing non-market interaction with entities outside the industry. In this sense, the system definition is narrower than in the national innovation system approach. Again, the main focus is on a static or comparative static analysis.

A similar approach is represented by '*sectoral innovation systems*' (Breschi and Malerba, 1997; see also Malerba and Orsenigo, 1990, 1993, 1995). As in Porter's analysis, the system definition here is based on 'industry' or 'sector'. But rather than focusing on interdependence within clusters of industries, sectoral innovation systems are based on the idea that different sectors or industries operate under different technological regimes which are characterized by particular combinations of opportunity and appropriability conditions, degrees of cumulativeness of technological knowledge, and characteristics of the relevant knowledge base. These regimes may change over time, making the analysis inherently dynamic, focusing on the competitive relationships among firms by explicitly considering the role of the selection environment.

Another system definition is built around the concept of *local industrial systems* as represented in AnnaLee Saxenian's (1994) study of the electronics industry in Silicon Valley in California and along Route 128 in Massachusetts. Here, the system definition is primarily geographical. The focus is on differences in culture and competition which have led to differences among the two regions in the degree of hierarchy and concentration, experimentation, collaboration, and collective learning which, in turn, have entailed differences in the capacity to adjust to changing circumstances in technology and markets. Thus, the analysis is inherently dynamic, but not in a formal sense.

Finally, the approach on which we will focus in more detail here is that based on the notion of *technological systems* (Carlsson, 1995, 1997). This concept is similar to Erik Dahmén's 'development blocs' (Dahmén, 1950, 1989) in that it is both disaggregated and dynamic: there are many (or at least several) technological systems in each country (thus, differing from national innovation systems [2]); and they evolve over time, i.e. the number and types of actors, institutions, relationships among them, etc. vary over time (thus, differing from all the other system definitions except Dahmén's). Also, national borders do not necessarily form the boundaries of the systems. In addition, the system definition focuses on *generic technologies*

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[2] It is, however, possible, at least in principle, to view a national system of innovation as the aggregate of a set of technological, sectoral, or regional systems.

with general applications over many industries, thus, distinguishing it from all the other approaches.

Technological systems involve market and non-market interaction in three types of network: buyer–supplier (input/output) relationships, problem-solving networks, and informal networks. While there may be considerable overlap between these networks, it is the problem-solving network which really defines both the nature and the boundaries of the system: where do various actors in the system turn for help in solving technical problems? Buyer–supplier linkages are important, the more so the more technical information is transmitted along with the transactions and less so, the more commodity-like the transactions are. Sometimes the most important technical information comes from sources (e.g. universities and research institutes) separate from buyers and sellers. Sometimes the informal, mostly personal, networks established through professional conferences, meetings, publications, etc. are important channels of information gathering and sharing.

A closely related concept is that of *competence blocs*. Competence blocs are defined primarily from the demand (product or market) side as the total infrastructure needed to create, select, recognize, diffuse, and exploit new ideas in clusters of firms (Eliasson and Eliasson, 1997, p. 14). An example is the competence bloc for health care in Sweden (see Eliasson, 1997). This bloc can be viewed as consisting of parts of several technological systems supplying technological artifacts applicable in the health care sector.

In applying the technological systems approach we start with the following four basic assumptions:

1. The system as a whole (rather than its individual components) is the primary unit of analysis; this is similar to several of the other systems approaches.
2. The system is dynamic, i.e. we need to take feedback explicitly into account. This becomes especially important in our approach, since we are interested in the evolution of the system over time.
3. Global technological opportunities are practically unlimited, i.e. the contribution of the system to global knowledge is quite modest; the main focus is on how well the system can identify, absorb, and exploit global technological opportunities. This means, e.g. that it may be more important to raise absorptive capacity than to create new technology.

4. Each actor (component) in the system operates with bounded rationality: actors are rational, but act under constraints of limited capabilities, information, etc. This is especially important in view of the vast global opportunity set.

4. Methodological issues

There are a number of methodological issues which arise in the application of the analytical framework of technological systems. The framework is still fairly loosely defined and several methodological alternatives are available. In this section, we will focus primarily on technological systems, but the issues are similar in other systems approaches as well. Our aim is to contribute to the discussion of methodology with respect to the analysis of innovation systems.

In our studies of technological systems over the last decade, there are three methodological issues which stand out as the most problematic. The first is the *level of analysis* to which a system approach is applied. A second is how we define the system *boundaries*, i.e. how to delineate the system and identify the actors. A third is how we can measure the *performance* of the system.

4.1. The level of analysis

The technological system framework was defined originally as a network of agents interacting in a specific technology under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology (Carlsson and Stankiewicz, 1995, p. 49). This definition opens up for a number of different ways to delineate the system, each involving a different *level of analysis*. We have found that the system approach may fruitfully be applied to at least three levels of analysis: to a *technology in the sense of a knowledge field*, to *a product or an artifact*, or finally to a *set of related* products and artifacts aimed at satisfying a particular function, such as health care or transport (this third level of analysis is henceforth labeled *a competence bloc*, see Eliasson, 1997). [3]

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[3] A fourth unit of analysis is a set of related firms (vertically or horizontally linked) operating on different markets and serving different functions. This is the unit of analysis employed by Porter (1998) in cluster analysis.
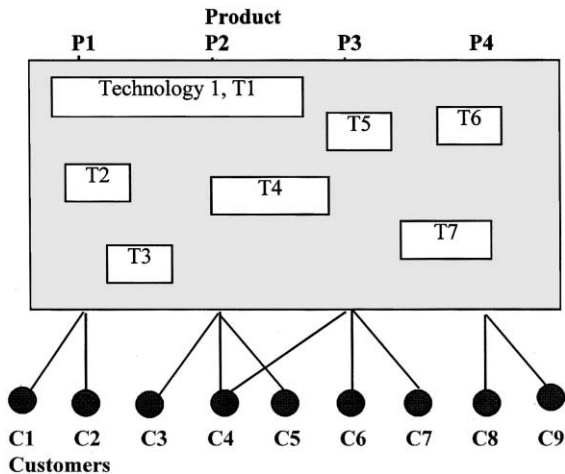
Fig. 1. Illustration of the three levels of analyses.

The differences between these three approaches is schematically shown in Fig. 1 where the 'columns' indicate products (P1, P2, etc.), the 'boxes' technologies (T1, T2, etc.) which are used within these applications, and the circles the customers (C1, C2, etc.) which the products aim to address. To delineate the system we may take as a starting point a specific technology (or set of closely related technologies), in the sense of a specific knowledge field, and analyze it in a certain application or in all its uses (e.g. technology T1 is used in product P1 as well as in P2 and P3). An example of a knowledge field may be digital signal processing, which may be used in a number of different products (e.g. mobile phones, control systems, etc.). Even though the process in which the technology is diffused into these products is analyzed, the products are not the main focus when this level of analysis is applied. Instead, we may penetrate the relation between technologies and the diffusion of technologies into different applications. For instance, Holmén (1998) studied microwave antenna technology which is incorporated into many and highly diverse products including mobile phones, microwave ovens, military radar and automatic doors. The customers included will be all those for which this technology is important. For example, if technology T1 is object of the study, parts of customer groups C1–C7 may have to be considered.

The second level of analysis is when we take a product as the initial seed from which the system is defined.

For example, an industrial robot (say P1 in the figure) consists of a number of technologies, e.g. drive, sensor and control technologies (T1, T3 and T4 in the figure), but the technologies are not the main focus when this level of analysis is applied. Instead, it is the artifact which is studied, and we want to study the links to its customers (in this case customer groups C1 and C2). If we instead are interested in a specific market and the system of actors and institutions supplying products to this market, we need to use the third level of analysis. This is the multi-product case where the focus is on a set of products (complementary or substitute) which are related by having a common market, say the health care market, operate under the same institutional arrangement, and therefore, share a common selection environment. In Fig. 1, products 1–4 could all be in the health care market, and we would include all products as well as all technologies in the analysis. (This level of analysis has been termed a competence bloc.) In such a study, we may analyze relations between products, between all customers groups, and also between the customers. However, the competence bloc will include a vast range of technologies and it will not be feasible to have a detailed analysis on the technological level.

Our first empirical work focused on factory automation equipment such as numerically controlled machine tools and industrial robots (Carlsson, 1995). The technologies involved were, for instance, control engineering, software engineering, and machine design. Hence, we ended up using a *product* as the level of analysis.

As a part of our research after this initial study, some members of our team took a direction where the level of analysis was constituted by a technology, in the sense of a knowledge field. This approach was pursued in Granberg (1997), Holmén and Jacobsson (1998), Holmén (1998) as well as by Rickne (2001), Laestadius (2001) and Fridh (2001). Another direction of research was towards the multi-product case, the competence bloc (Eliasson, 1997).

Thus, the system boundaries, the actors involved, the networks and institutions may vary depending on how we choose the level of analysis. With technology as the level of analysis, on the other hand, we will include all those entities having competence within a certain technological field (e.g. control engineering), regardless of in which application (products,

such as robots and fighter planes) they have used this competence. Taking a product focus, the actors are all within a given industry (e.g. the machine tool industry). Finally, a competence bloc as the level of analysis would include actors from several industries.

By focusing on technology in the sense of a specific knowledge field, we clearly cut a different 'slice of the cake' than had the (multi-technological) product been chosen as the level of analysis. This is illustrated in Holmén and Jacobsson (1998). This study attempted to identify the actors in a technological system where the level of analysis was microwave antenna technology. Altogether, over the 20 years covered, a total of 35 firms and other actors were identified at one time or another as belonging to the system in the sense that they were judged to have the capability to develop microwave antenna technology. The 27 firms (eight actors were individuals or institutions) were classified in as many as 11 three-digit industries (SNI 92). [4] Only four of the actors were classified in industry classes 322 (manufacturing of radio and TV transmitters, and apparatus for wired telephony and telegraphy) or 323 (manufacturing of radio and TV receivers, and apparatus for reproduction of audio and video signals) which pertain to telecommunication and which would be the first industries to look for firms mastering this technology. The others were in a wide range of other industries. Similar observations can be made for other technology-based clusters such as those based on polymers and biomedicine which also cut across industries.

The choice of unit of analysis partly reflects the nature of the questions raised. Referring back to the definition of technological systems as "... generating, diffusing and using technology...", a knowledge-based approach (the first level of analysis) would tend to be more concerned with technological problem-solving activities and the generation of new competence and knowledge (see for instance Granberg, 1995) whereas a product focus would tend to be chosen when the primary interest is in diffusion and use of new technology, see for instance Carlsson and Jacobsson (1993).

4.2. System boundaries: the delineation of a technological system and identification of actors

The second issue which we have encountered in our work is how to delineate the systems, i.e. setting the boundaries of the system. When the focus is on a product group or set of vertically related product groups, as is often the case within the context of National Innovation Systems or Porter's 'diamond', the delineation seems not to be a large issue as standard industrial and trade classifications can be used (Porter, 1990). A case in point would be the forest cluster in Finland which consists of key products such as paper and pulp and upstream and downstream industries such as paper machines and printing plants (Ylä-Anttila, 1994). Another example is our earlier work on factory automation (Carlsson, 1995). Still, if the ambition is to include a whole cluster of related firms, there is always the issue of where the boundary of the system lies. There is no reason to hide that the delineation may often be somewhat arbitrary and partly based on informed guesses by the researcher (Porter, 1998). [5]

Delineating the technological system is more difficult when the level of analysis is a specific technology. Three issues are at hand, each of which will be discussed below.

4.2.1. What is a technology, i.e. what falls within a particular knowledge field?

To be able to delineate the system, we need to understand what are the boundaries of the knowledge field studied, i.e. what falls inside and outside a particular knowledge field. Using technology as the level of analysis necessarily involves making such judgments in the process of delineating the technological system. This can, of course, not be done unless the researcher is familiar with the technological field and interacts a great deal with technological specialists.

One way of doing this would be to assess the distance in terms of knowledge between various technologies and set a 'break' point in this contin-

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[4] An 'industry' is broadly equivalent to the four digit level in ISIC, e.g. 35.1 'building and repair of ships and boats'.

[5] As Porter (1998, p. 202) puts it: "drawing cluster boundaries is often a matter of degree, and involves a creative process informed by understanding the most important linkages and complementarities across industries and institutions to competition. The strength of these 'spillovers' and their importance to productivity and innovation determine the ultimate boundaries".

uum. Several attempts have been made to measure 'technological distances' formally, i.e. to assess the 'closeness' of one technological field to another and, hence, to determine what falls within a particular knowledge field (Granstrand and Jacobsson, 1991, Ehrnberg and Sjöberg, 1995). However, these measures are quite aggregated and provided little assistance when judging whether or not, for instance, microwave antenna technology is within the same knowledge field as optical and radio frequency technologies or microwave-related components (Holmén and Jacobsson, 1998).

A possible way to approach the problem whether or not sub-technologies a and b are part of the same knowledge field is to assess the *amount of retraining* that engineers specialized in one of these fields need in order to be able to make a contribution to the other. In the particular case mentioned above, interviews with engineers suggested that although electrical engineers are able to participate in both optical and microwave technologies, there is clearly a need for retraining and learning as an engineer moves from one field to the other. A similar conclusion was reached for the field of radio frequency. This method involved expert judgments which can be supplemented by formal analyses of bibliometric and patent links at a very disaggregated level (Grupp, 1996).[6] Many citations or co-classifications between different categories would suggest a 'closeness' in terms of the underlying knowledge fields whereas a 'distance' would be assumed to exist where no citations or co-classifications are found.

Whereas it is, therefore, possible to demonstrate that differences exist among various knowledge fields, setting the precise borders of a competence field will always be somewhat arbitrary. Nevertheless, it is important to use a consistent and explicit method for doing so.

4.2.2. How do we deal with the dynamic character of a system?

A technological system is not static but evolves with alterations in the content of technologies and products as well as in the relationships among various technologies. Over time, *new* sub-technologies may emerge

and need to be included in the system. The boundaries as well as the relevant *complementary technologies* (technologies that combined with the original technology make a product) may well change as a technology evolves. Due to this dynamic character of the underlying competence base the system borders may need to be broadened (or in other cases narrowed), perhaps leading to a change in the set of actors (components), relationships, and attributes to be included.

For instance, in biomaterials there has been a shift of emphasis from synthetic to biological materials, and the delineation of the field has changed due to the introduction of new competence within e.g. biotechnology (Rickne, 2001). In this case, the relation between sub-technologies has shifted, resulting in links between synthetic and biological materials. Even specialists may not be in agreement as to what sub-technologies to include at any given point in time. The dynamic nature of systems may, therefore, imply considerable empirical problems.

Indeed, in extreme cases, a pervasive new generic technology may transform the whole knowledge base of an industry and lead to fundamental changes in the actors, networks and institutions supporting the industry. This may well be what we are beginning to see in the paper and pulp industry where biological processes are experimented with and may eventually substitute for chemical and mechanical processes (see Laestadius, 2001).

The inclusion of new sub-technologies in a given knowledge field can be illustrated also by the case of microwave antenna technology (Holmén, 1998). With the rapid diffusion of mobile telephony, a need arose to use the frequency spectrum more efficiently. This led to the development of 'intelligent' antennas which enable operators to get a higher transfer capacity in existing mobile communication systems. A pre-requisite for this was, however, the development of new digital signal processing algorithms. These were integrated with the antenna technology and enlarged the technological field of microwave antenna technology.

This was made economically feasible only due to the parallel development in semiconductors which demonstrates the relevance of the need to handle *complementary technologies*. Granberg (1988) illustrates this further in the field of fiber optics. The economic exploitation of fiber optics, and indeed, the interest by various actors in developing fiber optics technology,

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[6] This particular study was done at an aggregated level, but could be undertaken at a less aggregated level.

depended on the parallel development of laser technology. Hence, if we want to use a system approach to unravel the process of innovation and diffusion in fiber optics, leaving the complementary technology of laser out of the picture, would mean that we would lose explanatory power. Likewise, many biomaterials applications have depended on the parallel progress of complementary products. An example is the development of an artificial pancreas where the evolution now is spurred by advances in biosensors giving the possibility to measure glucose levels in the body (Rickne, 2001).

Hence, in longitudinal or historical studies we may need to redefine the boundaries of the system as it evolves. There is, therefore, no unique and always valid way of delineating a technological system. This does not, of course, make the empirical delineation any simpler.

4.2.3. Identifying the actors

Finding the actors in a technological system is, of course, a key objective for the researcher. There are at least two issues involved in identifying them. First, how do we know that a specific actor belongs to the system and, second, how do we find all actors in the system?

If we use a product as the level of analysis, identifying the actors is not a major problem as firms are allocated to specific industrial sectors by the statistical offices.[7] Input/output tables and production and trade statistics can be used. There are also industry associations and other organizations which have an interest in cataloguing firms in a specific product area. Care must, however, be taken in comparative studies where industry associations in different countries may have different degrees of success in organizing the industry and may set different industry borders.

While using membership lists from industry associations and the like is a standard method for identifying firms in a particular industry or product area, that method is of less use when a particular field of knowledge is applicable to many product areas,

some of which are unknown to the researcher. We, therefore, need another method for identifying firms competent in a specific knowledge field.

Mapping the competence base of firms is commonly done with the use of patents (e.g. Miyazaki, 1994; Jacobsson et al., 1995; Praest, 1998). However, there are at least three problems involved in using patents, apart from those conventionally listed (Pavitt, 1988).[8] First, a general problem with patent-based methods to identify a population on knowledge-based criteria is that the US patent classification system is not always structured around specific knowledge areas.

Quite frequently, the classes are functionally based. For instance, one patent class is 'electric heating' which includes many ways by which electricity is used to heat, including microwave heating. The class can also be product-based, such as medical equipment, which then may include products based on very different technologies.

Second, patent holding does not necessarily reflect a deep knowledge in a particular knowledge field. Holmén and Jacobsson (1998) distinguished between firms *applying* microwave antenna technology and those *developing* the technology, where only the latter makes a firm eligible. In order to find all firms with the required capabilities to develop the technology they used patent analysis. However, it was not enough to take the appropriate class and to identify the firm's granted patents in that class. Some of the patentees simply applied the technology and the patent, therefore, did not really reflect any deep knowledge in microwave antenna technology. For instance, the innovative part in a patent was, in one case, a mechanical structure, but the patent was *co-classified* in a microwave antenna class. Hence, a scrutiny of each patent application was needed to select the eligible firms.

Third, patents reflecting knowledge to develop a particular technology, for instance microwave technology, may be found in many classes and a quite elaborate method may need to be devised to identify these (see, for instance, Holmén and Jacobsson, 1998). Efforts to use patents may, of course, not always be successful. In the case of biomaterials,

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[7] At least this is true if we ignore the inherently somewhat arbitrary nature of industrial classifications. Some classifications are based on type of product, others on technology, and yet others on type of inputs. Sometimes all the three criteria appear in the same system.

[8] Such as variance in the propensity to patent between firms and the difficulties to map technological activities in software by using patents.

Rickne found no classes specifically allocated to biomaterials. Rickne then looked at the patent classes used [9] by already identified biomaterials actors. These classes were then combined with keywords in order to sort out the relevant actors. However, the method gave a very broad spectrum of actors, of which only a few were active in biomaterials. Instead, Rickne developed a method whereby she started with the key patents in the different parts of the biomaterials field and then identified those actors which cited these patents. This method turned out to be successful.

The so-called 'snowball method' can be used independently of the level of analysis applied. It simply means that, starting from either a technology or a product base, each actor is asked to point to further participants. The method assumes that the firms or other actors are aware of at least some other actors who master the specific technology area. This may not always be true, of course. Another problem is that the number of actors may expand and exceed the practical limitations of the study.

Of course, it may be useful to apply several methods simultaneously, given the inherent uncertainties in each method. For example, Rickne (2001) combined three methods. Biomaterials technology can be incorporated into many products. The first step was to identify these products and consult industry associations and directories for firms producing them. Second, interviews with these firms and associations pointed to further actors (researchers, firms, organizations) which in turn were contacted (snow-ball). Third, citations of important inventions verified and broadened the set of actors. Also Holmén and Jacobsson (1998) supplemented the snowball method with a patent-based method in order to reduce the risk that the population was not fully identified. Indeed, in the patent-based method, they identified a few actors which the snowball method had missed.

4.3. System performance: how can we measure the performance of a technological system?

A technological system has a number of different types of actors: firms, organizations, policy bodies, venture capitalists, etc. To evaluate the performance of a system, therefore, means to evaluate each of these players, not primarily as single entities, but connected in the entire system. All parts must be of a certain size and quality in order for the system to function well. [10] Therefore, when interested in the performance of an innovation system, we may evaluate how each individual part of a system performs (e.g. the firms, the educational system, [11] and the capital market), but the main focus is on the performance of the total system. [12]

The exact choice of performance measure is complicated and depends on (1) *the level of analysis applied* as well a on (2) *the maturity* of the system.

1. As mentioned above, when a particular knowledge field constitutes the *level of analysis*, the objective of the exercise tends to be to uncover the process of generation and diffusion (see the definition of technological systems) of knowledge, for instance in the cases of antennas (Holmén, 1998), ceramics (Granberg, 1993), and combustion (Granberg, 1997) technology. Whereas the performance of this process may be assessed via patent and bibliometric studies, it is quite difficult to measure the economic performance associated with the use of that knowledge. This is so for three reasons. First, only rarely is a particular knowledge field economically useful on its own; it needs complementary technologies [13] in order to form various types of products. Second, any given knowledge field probably enters a broad range of industries, but may play just a minor role in each of them. Third, the role of a given knowledge field may change rapidly over time, but in an uneven fashion in different industries.

   Measuring the performance of a system seems to be a great deal easier if the level of analysis is a product, industry or group of industries (a compe-

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[9] Patented or cited when the technology was licensed.

[10] Sometimes a weak part of the system may be compensated for by another part of the system.

[11] For example, Jacobsson (1997) assessed the performance of the Swedish universities in terms of graduating engineers with a background in electronics and computer science, and contrasted this performance with that of other countries. The result was used as part of an explanation for the relative weakness of the Swedish electronics industry in the 1980s and early 1990s.

[12] It may, however, be quite difficult to measure performance at the system level, making it necessary to rely instead on a series of partial measures (at the sub-system level).

[13] As discussed above, in the delineation phase of a study, such complementary technologies need to be identified.

Table 1
Examples of performance measures for an emerging technological system[a]

Indicators of generation of knowledge	Indicators of the diffusion of knowledge	Indicators of the use of knowledge
Number of patents	Timing/the stage of development	Employment
Number of engineers or scientists	Regulatory acceptance	Turnover
Mobility of professionals	Number of partners/number of distribution licenses	Growth
Technological diversity, e.g. number of technological fields		Financial assets

[a] Source: Rickne (2001).

tence bloc). In our early work on factory automation (Carlsson, 1995), the main performance indicator was the extent of *diffusion* of factory automation in Sweden, as compared to other countries, using conventional diffusion analysis. [14] Keeping the product, or industry, as the unit of analysis we could, in later studies (Carlsson, 1997), use patents to calculate the *revealed technological comparative advantage* in, say, electronics, as an indicator of the *generation* of knowledge and conventional performance indicators of the *use* of technology, such as *market shares and exports*. These types of indicators can also be used when the unit of analysis is a competence bloc. Hence, satisfactory ways of measuring the performance in terms of the generation, diffusion and use of technology, in the sense of an artifact, are available.

2. For an *immature* system, the measurement problems are greater. We perceive that a single indicator is not sufficient to capture performance and, therefore, that several measures have to be combined to give an assessment of the performance in what may be called the fluid phase (Utterback, 1994) of a system. In particular, indicators of performance in terms of both generation of knowledge and the diffusion and use of that knowledge are important to incorporate. Below, we sketch some possible measurements that may be combined for an effective evaluation (see Table 1). None of these measurements alone can describe the performance, but combined they may give a more complete assessment of how well an emerging system is performing.

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[14] It was a superior performance in Sweden which we aimed to explain using a system approach (for a summary, see Carlsson and Jacobsson, 1997).

The indicators are drawn from Rickne (2001) who studied firms active in a set of young and science-based technologies, namely, biomaterials which is a sub-set of the biomedical field.

The ability of the system to generate knowledge is assessed using four indicators. The first is the conventional patent indicator, revealing the volume and direction of the technological capabilities in the system. A related, and second, indicator is the number of scientists and/or engineers active in the technological fields. Not only the volume of activities matters, but also cross-fertilization of different technologies, ending up in new and difficult-to-foresee combinations of knowledge. Here, the mobility of professionals, with a subsequent diffusion of their knowledge into new technological fields, may be a performance indicator (Rappa, 1994). The fourth indicator is even less conventional. There is often a large uncertainty regarding which of a whole range of technological approaches will succeed in reaching the market in an immature system. This is particularly so in the field of biomaterials. With great uncertainty, evolutionary theory emphasizes the need for experimentation in a system. Technological (and scientific) diversity may, therefore, be considered as an indication of system performance as it presumably reflects the robustness of the system to the outcome of a selection process, and consequently, its growth potential.

As the technology is science-based, product development requires a great deal of time. Developing products for a medical device or pharmaceutical market requires clinical trials, and regulatory issues further delay market entrance, i.e. the *diffusion* process from the lab to the market is lengthy. Thus, an evaluation of the 'closeness' to market exploitation was deemed to be appropriate. Rickne employed two

different market-related measures of performance. First, she assessed whether or not the product had received regulatory acceptance by government authorities. Second, as the majority of the companies within this section of the biomedical industry need an agreement with a partner in order to have access to distribution channels, the number of partners was used as an indicator of closeness to market exploitation.

Finally, conventional indicators of the economic use of knowledge can be used, such as employment, sales, and growth figures. In addition, the financial assets the firms have managed to raise, can be used as supplementary information of the ability to exploit knowledge commercially, indicating, e.g. 'staying power' as well as the interest in the firms from other companies or from the capital market.

To conclude, measuring the performance of a technological system is not straightforward, but requires a careful consideration of the level of analysis applied and the degree of maturity of the technological system studied. Several indicators rather than only a single one are preferable, in particular when it comes to assessing the performance of an emerging technological system.

5. Conclusion

In this paper, we have focused on some analytical and methodological issues which we have found to be particularly important in the analysis of technological systems, but which are also relevant in other approaches to innovation systems. These issues are, first, what is the appropriate level of analysis for the purpose at hand? Secondly, how do we determine the population, i.e. delineate the system and identify the actors and/or components? What are the key relationships that need to be captured so that the important interaction takes place within the system rather than outside? Thirdly, how do we measure the performance of the system: what is to be measured, and how can performance be measured at the system level rather than at component level?

The methodological issue which seems to us most in need of further work is that of performance measurement. Given the dynamic nature of innovation systems, measuring their performance at a particular time is not only problematic, but can also be misleading. The most important aspect of performance may be the extent to which the system contributes to long-term economic growth—which can only be assessed in retrospect.

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