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Analyzing the functional dynamics of technological innovation systems: A scheme of analysis

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Abstract

Various researchers and policy analysts have made empirical studies of innovation systems in order to understand their current structure and trace their dynamics. However, policy makers often experience difficulties in extracting practical guidelines from studies of this kind. In this paper, we operationalize our previous work on a functional approach to analyzing innovation system dynamics into a practical scheme of analysis for policy makers. The scheme is based on previous literature and our own experience in developing and applying functional thinking. It can be used by policy makers not only to identify the key policy issues but also to set policy goals.

Keywords: Innovation system; Dynamics; Functional analysis; Policy

1. Introduction

Scholars on innovation and technology have almost completely rejected the market failure approach as a basis of policy action. It is argued repeatedly in the literature (e.g. Malerba, 1996; Metcalfe, 1992, 2004; Smith, 2000) that the approach is flawed and insufficient. A systems approach to innovation is often seen as a more appropriate alternative. In particular, the concept of 'innovation system' has won the approval of an increasing number of academic researchers interested in the processes underlying innovation, industrial transformation and economic growth. The innovation system approach has also been adopted by regional and national authorities/agencies as well as by international organizations (e.g. the OECD, the European Commission and UNIDO) interested in stimulating these processes.

Various researchers and policy analysts have made attempts to study innovation systems empirically in order to describe and understand their structure, dynamics and performance. However, recent surveys of the literature (e.g. Edquist, 2004; Liu and White, 2001) have acknowledged the lack of comparability between these studies

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as well as the conceptual heterogeneity in the innovation system literature. Perhaps as a consequence of this, the innovation system approach has been criticized for not providing practical enough guidelines for policy makers (cf. Edquist, 2004; Klein Woolthuis et al., 2005). There is, thus, a need for a practically useful analytical framework that allows for the assessment of system performance as well as the identification of factors influencing performance.

This paper presents a scheme of analysis which addresses these issues and may be used by researchers, as well as policy makers, to analyze specific innovation systems in order to identify key policy issues and set policy goals. The contribution is twofold. First, the paper describes a systematic step-by-step approach to analyzing innovation systems, describing and assessing performance and identifying key policy issues.[1] Second, and most important, the paper presents a framework that not only captures the structural characteristics and dynamics of an innovation system, but also the dynamics of a number of key processes, here labeled 'functions', that directly influence the development, diffusion and use of new technology and, thus, the performance of the innovation system. The functions have been synthesized from a number of different system approaches to innovation and provide a basis for performance assessment as well as comparison between different innovation systems in terms of system dynamics.

The paper is organized as follows. In Section 2, we position ourselves in the innovation system literature and explain how our approach on functions in innovation systems was developed. In Section 3, we outline the scheme of analysis. Section 4 summarizes our conclusions and presents some recommendations for further research.

2. Positioning and development of the analytical approach

2.1. Innovation system as an analytical construct

A general definition of a system is a group of components (devices, objects or agents) serving a common purpose, i.e. working towards a common objective or overall function. The components of an innovation system are the actors, networks and institutions (Carlsson and Stankiewicz, 1991) contributing to the overall function of developing, diffusing and utilizing new products (goods and services) and processes (cf. Bergek, 2002; Carlsson and Stankiewicz, 1995; Galli and Teubal, 1997).

Although the system concept may suggest collective and coordinated action, an innovation system is primarily an analytical construct, i.e. a tool we use to better illustrate and understand system dynamics and performance. This implies that the system in focus does not have to exist in reality as fully-fledged. Instead, it may be emerging with very weak interaction between components.

Moreover, interaction between components may be unplanned and unintentional rather than deliberate even in a more developed innovation system. Using the notion of an "overall function" does not imply that all actors in a particular system exist for the purpose of serving that function or are directed by that function. Actors do not necessarily share the same goal, and even if they do, they do not have to be working together consciously towards it (although some may be). Indeed, conflicts and tensions are part and parcel of the dynamics of innovation systems.[2] Clearly, we do not see the system's components as directed or orchestrated by any specific actors.

A number of different innovation system concepts have been put forward in the literature, including national systems of innovation (Freeman, 1987; Lundvall, 1992a; Nelson, 1992), regional innovation systems (Asheim and Isaksen, 1997; Cooke et al., 1997), sectoral systems of innovation and production (Breschi and Malerba, 1997; Malerba, 2002) and technological systems (Carlsson and Stankiewicz, 1991).[3] There are also other similar socio-technical system concepts (cf. Bijker, 1995; Geels, 2004; Hughes, 1983). In this paper, we focus on *technological innovation systems* (TIS) (Bergek et al., 2007a), i.e. socio-technical systems focused on the development, diffusion and use of a particular technology (in terms of knowledge, product or both).[4]

[1] The scheme of analysis was developed as part of a collaborative project with VINNOVA (the Swedish Agency for Innovation Systems) (see Bergek et al., 2005). In this project we also analyzed three empirical cases ("IT in home care", "Mobile data" (see Lindmark and Rickne, 2005) and "Biocomposites") in collaboration with VINNOVA.

[2] Schumpeterian competition is a vital part of vibrant innovation systems, and firms and other actors also compete in shaping expectations of a technology and in building legitimacy for it.

[3] For an overview, see Carlsson et al. (2002) and Edquist (1997).

[4] The concept of technology incorporates (at least) two interrelated meanings. First, technology refers to material and immaterial objects – both hardware (e.g. products, tools and machines) and software (e.g. procedures/processes and digital protocols) – that can be used to solve real-world technical problems. Second, it refers to technical knowledge, either in general terms or in terms of knowledge embodied in the physical artifact. In line with Layton (1974) and Das and Van de Ven (2000), we include both of these meanings (i.e. both artifact and knowledge) in our definition of technology.

TISs do not only contain components exclusively dedicated to the technology in focus, but all components that influence the innovation process for that technology. A TIS may be a sub-system of a sectoral system (when the focus is one of the sector's products or a knowledge field that is exclusive to the sector) or may cut across several sectors (when the focus is a more "generic" knowledge field that several sectors make use of, e.g. microwave technology (see Holmén and Jacobsson, 2000)). TISs may have a geographical dimension, but are often international in nature.[5]

2.2. *Previous innovation system approaches to innovation policy*[6]

A central proposition in the systems literature on policy is that just as the nature of actors/markets may obstruct the formation of a TIS, so can institutions and networks (e.g. Carlsson and Jacobsson, 1997; Edquist, 1999; Malerba, 1996; Metcalfe, 2004; Rotmans et al., 2001; Unruh, 2000). Eventually, such weaknesses in system structure may lead to "system failure", i.e. a system that fails to develop or does so in a stunted fashion (Carlsson and Jacobsson, 1997).

Most of the literature discussing innovation system failure tends to focus on perceived weaknesses in the *structural* composition of a system. For example, all the four types of system failures identified by Klein Woolthuis et al. (2005) in their recent synthesis and re-categorization of previous system failure literature are related to structural components: infrastructural failures (related to actors and artifacts), institutional failures (related to institutions), interaction failures (related to networks) and capabilities failures (related to actors). However, it is difficult, if not impossible, to evaluate the "goodness" or "badness" of a particular structural element or combination of elements without referring to its effects on the innovation process. For example, how do we know whether the existence of a particular actor network is a strength (e.g. a source of synergy) or a weakness (e.g. a source of lock-in or "group-think") (cf. Klein Woolthuis et al., 2005), without identifying its influence on the innovation process and its key sub-processes?

Thus, in order to be able to identify the central policy issues in a specific innovation system, we need to supplement a structural focus with a process focus. In this paper, we present a framework outlining seven key processes – here labeled 'functions' – which have a direct and immediate impact on the development, diffusion and use of new technologies, i.e. the overall function of the TIS as defined above. It is in these processes where policy makers may need to intervene, not necessarily the set-up of the structural components (actors, networks, institutions). The functions approach to innovation systems thus implies a focus on the dynamics of what is actually "achieved" in the system rather than on the dynamics in terms of structural components only. This is, indeed, its main benefit: It allows us to separate structure from content and to formulate both policy goals and policy problems in functional terms.[7] We will return to this point.

2.3. *The development of the "functional dynamics" approach*

As noted previously, concerns have been raised with regard to the conceptual heterogeneity of the innovation system concept. This was one of the starting points of the functional dynamics approach presented in this paper: our first identification of a number of functions (Johnson, 1998[8]) was made in an attempt to see whether there was any agreement between different innovation system approaches with regard to what they described "happened" in the system and, if so, to identify the key processes that they agreed upon. A scrutiny of the received literature revealed that the system approaches indeed shared an understanding of a set of such basic "functions", defined as the contribution of a component or a set of components to the overall function of the innovation system (Johnson, 1998, 2001).[9]

The first list of functions/processes was, thus, identified through a scrutiny of a number of central innovation

[5] A TIS with a high degree of regional concentration comes close to the definition of a technological cluster or region (cf. Cantner and Graf, 2004; Maskell, 2001; Porter, 2000).

[6] This section is based on Bergek et al. (2007b).

[7] For example, the lack of research institutes has often been identified as a major problem in the Swedish National Innovation System, without much empirical evidence that this structural characteristic influences innovation processes in any important way. By focusing on functions, we could be able to analyze how research institutes in other countries influence the innovation process, and then see if this type of influence is absent in the Swedish system or if the same type of influence is present through another type of actor.

[8] Johnson was Anna Bergek's maiden name.

[9] It should be noted here that we use the concept of "functions" without any reference to the sociological concepts of "functionalism" and "functional analysis". Our analogy is instead technical systems, with "hard" system components filling different technical functions, thereby contributing to the system's overall (technical) function. As noted previously, the "overall function" is analytically defined and does not imply that actors exist for the purpose of serving that function or are directed by it.

system references, including work by Christopher Freeman, Richard Nelson, Charles Edquist, Bengt-Åke Lundvall, Bo Carlsson and Rikard Stankiewicz, complemented with literature on related concepts such as socio-technical systems (e.g. Wiebe Bijker and Thomas P. Hughes), development blocs (e.g. Eric Dahmén) and industrial networks and clusters (e.g. Håkan Håkansson and Michael Porter). The processes described in this literature were categorized into a list of eight functions (Johnson, 1998).[10] A similar list of functions was later developed through an empirical study of the biomaterials industry (Rickne, 2000).

Through empirical application,[11] additional literature studies and discussions amongst ourselves and with other researchers pursuing similar approaches, the list has been revised and refined several times. We have added insights from political science (e.g. Sabatier, 1998), sociology of technology (e.g. Kemp et al., 1998) and organization theory (e.g. Van de Ven, 1993), which in particular have highlighted the political nature of the innovation process and the importance of legitimation. The current framework, which we present in detail later on in this paper, includes seven functions on which there is quite large agreement between different functions approaches (see Appendix A for a description and comparison of various contributions).[12]

Since the framework presented here is based on previous literature, it is perhaps reasonable to assume that a "conventional" innovation system analysis would identify the same processes (although termed differently). However, this does not seem to be the case. First, Edquist (2004) identifies a number of "activities", defined as "those factors that influence the development, diffusion, and use of innovation" (p. 190). Some of these activities are, however, structural in nature (e.g. "creation of organizations"). Moreover, since several of the activities are much more specific in nature than our functions (e.g. "incubator support" vs. "resource mobilization"), they do not cover all aspects of our functions (see Appendix A). Second, in a recent paper (Bergek et al., 2007b) we concluded that although most of our functions were mentioned in the "Policy and innovation system" literature of the 1990s (largely), none of the literature we reviewed mentioned all functions at the same time. Instead, policy researchers seemed to focus on a few functions or on general policy problems to be solved, often in an unsystematic way and without stating any clear reason for that particular focus.[13] In addition, two of our functions ('development of positive externalities' and 'legitimation') were either mentioned in passing or completely left out, which is surprising since their importance has been noted in several other strands of literature that we have reviewed. Here lies the main difference between the functions approach and "conventional" innovation system analyses with respect to key processes: explicitly stating and including all functions, which allows for the systematic identification of policy problems. It should be noted, though, that this list of functions may require further revisions as and when the research on innovation system dynamics provides new insights.

3. The scheme of analysis

A scheme of analysis is a description of a number of sub-analyses – in the following referred to as "steps" – that need to be taken by the analyst. Our approach implies that the analyst needs to go through six such steps (Fig. 1). The first step involves setting the starting point for the analysis, i.e. defining the technological innovation system (TIS) in focus. In the second step, we identify the structural components of the TIS (actors, networks and institutions). In the third step, we move from structure to functions. With an analysis of functions, we first desire to describe what is actually going on in the TIS in terms of the seven key processes where we come up with a picture of an "achieved" functional pattern, i.e. a description of how each function is currently filled in the system. The subsequent fourth step is normative; we assess *how well* the functions are fulfilled and set process goals in terms of a "desired" functional pattern. In the fifth step, we identify mechanisms that either induce (drive) or block a development towards the desirable functional pattern. We can then specify key policy issues related to these inducement and blocking mechanisms, and this is the sixth and final step.

It should be noted that the analysis will most often not proceed in a linear fashion (as the focus on "steps" might suggest). In contrast, the analyst has to expect a great number of iterations between the steps in the process of the analysis. For reasons of simplicity, however, we will discuss the six steps sequentially.

[10] We searched for references of things that "happened", took place or "were done" (by any component) in the innovation system. All these were typed into categories that were assigned a label. These labels were used as names for the first functions.

[11] See Bergek and Jacobsson (2003), Jacobsson and Bergek (2004), Jacobsson et al. (2004), Bergek et al. (2005), and Hekkert et al. (2007).

[12] We do not claim this to be a complete and final set of functions. Additional studies will have to refine and possibly add to the list.

[13] Malerba (1996) and Carlsson and Jacobsson (1997) are the main exception, covering most of our functions.

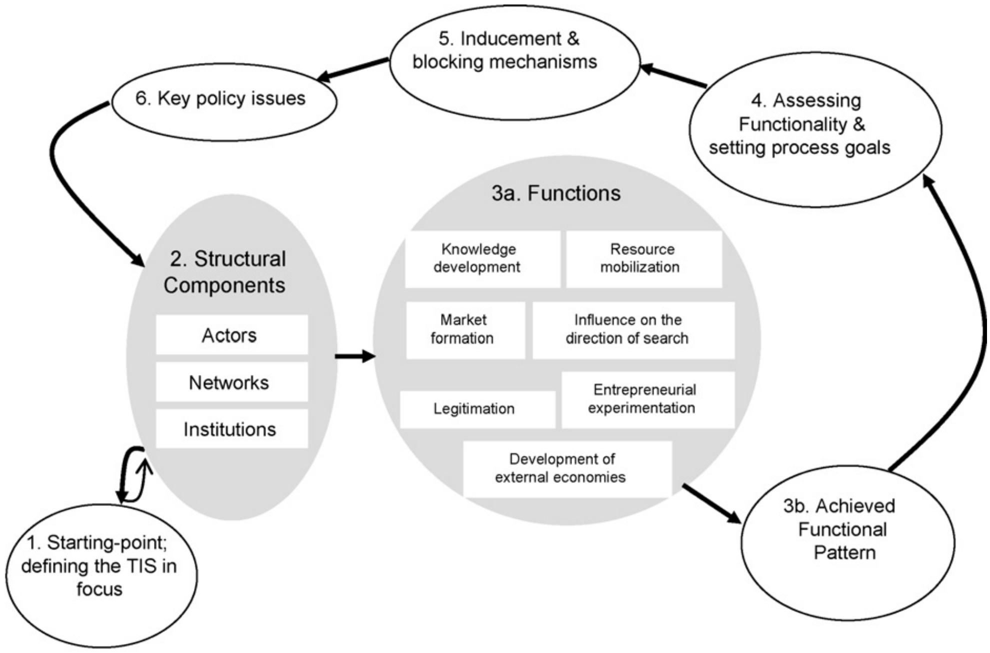

Fig. 1. The scheme of analysis (adapted from Oltander and Perez Vico, 2005).

In the following, we will articulate the analytical content as well as some methodological opportunities and problems for each step. We use a number of empirical examples to illustrate our reasoning. These should be seen as "light" illustrations rather than empirical evidence of the validity of the framework.[14]

4. Step 1: the starting point for the analysis: defining the TIS in focus

The empirical operationalization of the TIS concept is not always as straightforward as it may seem at a first glance. Indeed, analysts face several choices when it comes to deciding the precise unit of analysis – or focus – of the study. The outcome of these choices determines what particular TIS is captured, with respect to both structure and functions, and it is therefore crucial to make a *deliberate* choice, to *re-evaluate* this throughout the analysis, to *draw conclusions* as to how the choice of starting point has affected the picture painted, and to *communicate* the unit of analysis clearly to the recipients of the analysis, be they policy makers or other researchers. Nevertheless, this is often neglected in empirical analyses, and the failure to make explicit the precise unit of analysis seems to be one reason why it is difficult to compare the results of different studies.

We will outline three types of choices that analysts need to consider: (1) the choice between knowledge field or product as a focusing device, (2) the choice between breadth and depth, and (3) the choice of spatial domain. In this, there is no one correct choice – the starting point depends on the aim of the study and the interests of the involved stakeholders (e.g. researchers or policy makers).

It follows from our definition of technology (see also footnote 4) that the focus of attention may either be a *knowledge field or a product/artifact*, and the analysis first involves choosing between these two as the starting point. One common – and straightforward – starting point for the analysis is in terms of a product or product group, for instance a wind turbine (Bergek and Jacobsson, 2003) or a machine tool (Carlsson and Jacobsson, 1993). Another option is to start the analysis in a technological knowledge field (Holmén and Jacobsson, 2000). A researcher will presumably choose a focus that reflects the nature of the question raised, whereas policy makers will choose a definition that suits their area of responsibility, which for example may be a knowledge field, a particular product or a product group.

Having decided on product vs. knowledge field as a practical way of proceeding, we need to choose *breadth of the study*. A first choice concerns *the level of aggregation* of the study. This is relevant for both alternatives but is most prominent when dealing with a particular

[14] Most examples draw from longer texts of ours that are available: Holmén and Jacobsson (2000), Rickne (2000), Bergek and Jacobsson (2003), Jacobsson and Bergek (2004), Jacobsson et al. (2004), Lindmark and Rickne (2005) and Jacobsson and Lauber (2006).

knowledge field. In addition, focusing on a knowledge field involves determining the *range of applications* in which the technology is relevant. Let us elaborate on these two points.

First, a decision on the level of aggregation of the study means that we choose between including much, in order to get a broad picture, or being more specific, in order to be able to go more into detail. Certainly, the definition of the knowledge field to study may be very narrow (e.g. stem cells) or much broader (e.g. IT). It may also be defined as *one* specific knowledge field (e.g. microwave technology; see Holmén and Jacobsson, 2000) or as a *set of related* knowledge fields (e.g. biocompatible materials; see Rickne, 2000).[15]

Second, there is a choice of *the range of applications* of the technology in question that should be included in the study. The analysis may be limited to its use in specific applications, products or industries. Take the emerging application of "IT in home care", where a TIS may be defined by the use of a generic technology (IT) in a particular application: care of elderly and ill people in their homes instead of in a hospital. Here, a certain application dictates what actors, networks and institutions will be included in an analysis. In other cases, the study may include all possible applications. This was, for instance, done by Holmén and Jacobsson (2000) for microwave technology.

To illustrate further the need to make deliberate choices regarding the focus of the TIS, we may take the case of an analyst interested in the emerging field of biocompatible materials and the associated products of bio-implants, drug delivery and artificial organs. Such a TIS may be defined in terms of the products or by the underlying knowledge fields. If the second alternative is chosen, the analysis could be focused on some of the underlying technologies (e.g. some types of biopolymers) or on all of them. Furthermore, the boundaries of the system could be set to some specific applications (e.g. medical applications) or all (e.g. include also environmental applications; see Rickne, 2000). Depending on the choices made, different sets of actors, networks and institutions will be incorporated, and thus we capture different TISs or see different parts of the overall picture.

Finding the appropriate focus may not always be straightforward. When the analyst is new to a case, it may be necessary to have a broad starting point, and narrow it down as the understanding of the TIS increases and narrower potential foci are identified. For example, in an earlier study two of us analyzed the larger, product group based, Swedish TIS for renewable energy technology (including, e.g. wind turbines, solar cells, solar collectors and bioenergy) (see Johnson and Jacobsson, 2001), after which we narrowed our focus and analyzed the TIS for wind turbines (see Bergek and Jacobsson, 2003). The first step was necessary for us to begin to understand the features of the field of renewable energy in general, without which we would not have been able to continue with our in-depth case study of wind turbines.

In addition, given the large uncertainties involved when the analysis concerns an emerging TIS, a definite focus may be difficult to choose and may have to be changed over time. Sometimes, the initial expectations may prove to be quite wrong. For instance, the early development of laser technology was expected to find its main application in space warfare, while later the main application proved to be in CD players. Any early focus should therefore be seen as a "snapshot" valid only at a particular point in time. As the analysis unfolds, and as time passes, we may learn that the initial focus needs to be altered.

As noted in Section 2.1, the analysis does not require the focal TIS to exist in reality as a system: An emerging TIS may be analyzed as well and it may, indeed, even be possible and fruitful to analyze a TIS that only exists as an idea. For example, the Swedish TIS for biocomposites[16] today only exists in the form of a number of separate sub-systems, each closely related to one application (e.g. packaging or furniture). From a policy perspective, however, it seems to make sense to work towards integrating these into one overall TIS, since this may increase learning, knowledge development and, thereby, the rate of development of the system as a whole. A TIS may therefore be defined as an analytical construct incorporating hitherto disconnected sub-systems and guide policy makers in their decisions.

Having made the choices specified above, the study may also – as a complement – have a *spatial focus*. While TISs are generally global in character, there may be reasons to focus on a spatially limited part of a particular

[15] Technical change often involves the combination of many technologies and complementary products/services, which all need to evolve for the value of an initial innovation to materialize. This implies that no matter how narrow or broad the starting point of the analysis is, the analyst needs to be aware of and include related dynamics.

[16] A composite is a combination of two or more distinct materials, usually some type of fibers and a resin matrix. The concept of 'biocomposites' refers to composite materials, where all input materials are renewable in contrast to conventional composites, which are petroleum-based. There are also hybrid forms, for example "wood plastic composites" that consist of wood fibers in a petroleum-based matrix.

system in order to capture other aspects, perhaps those most relevant for a particular set of actors in a national or regional context. However, a geographical delimitation should not be used alone. Moreover, an analysis always needs to have a strong international component simply because a spatially limited part of a global TIS can neither be understood, nor assessed, without a thorough understanding of the global context.

5. Step 2: identifying the structural components of the TIS

Having decided on the focus of the TIS (in a preliminary way), the next step is to identify and analyze the structural components of the system. First, the *actors* of the TIS have to be identified. These may include not only firms along the whole value chain (including those up- and downstream), universities and research institutes, but also public bodies, influential interest organizations (e.g. industry associations and non-commercial organizations), venture capitalists, organizations deciding on standards, etc.

To identify actors in a specific industry, there are a number of available methods. Several of these normally need to be used:

- *Industry associations* are a good source, as are exhibitions, company directories and catalogues.
- A *patent analysis* may reveal the volume and direction of technological activity in different organizations and among individuals and may thus be a useful tool to identify firms, research organizations or individuals with a specific technological profile (see e.g. Andersson and Jacobsson, 2000; Holmén and Jacobsson, 2000; Rickne, 2000). Identification may take place even if the various organizations are not linked in any form (by markets or networks).[17]
- *Bibliometric analysis* (volume of publications, citation analysis, etc.) will provide a list of the most active organizations in terms of published papers, etc., and these organizations will include not only universities but also institutes and firms.
- *Interviews and discussions with technology or industry experts* ("gurus") as well as with firms, research organizations, financiers, etc., is a good way to identify further actors. This may be called a "snowballing" method to identify actors, where each actor may point to additional participants (see Rickne, 2000).

The second structural component of interest is that of *networks*, informal as well as formal. A number of different types of networks are relevant. Some are orchestrated to solve a specific task, such as standardization networks, technology platform consortia, public–private partnerships or supplier groups having a common customer. Other networks evolve in a less orchestrated fashion and include buyer–seller relationships and university–industry links. In this, some networks are oriented around technological tasks or market formation and others have a political agenda of influencing the institutional set-up (see e.g. Rao, 2004; Sabatier, 1998; Suchman, 1995). Social communities, such as professional networks and associations or customer interest groups, may also be important to map.

Formal networks are often easily recognized, whereas the identification of informal networks may require discussion with industry experts or other actors, or analysis of co-patenting, co-publishing or collaboration (e.g. joint ventures and joint university–industry projects). In the case of "mobile data",[18] the history of the Swedish TIS shows that networks between the two leading firms (Ericsson and Telia) and academic research groups have been prominent and have contributed to knowledge formation and diffusion (Lindmark and Rickne, 2005). Sometimes analysts have to look for subtle signs pointing to the existence or non-existence of networks. For example, given that academia and industry failed to communicate on a specific technical solution to an urgent industrial problem, we could conclude that learning networks were weak in the pellet burner industry in Sweden (Johnson and Jacobsson, 2001).

Third, *institutions* such as culture, norms, laws, regulations and routines need to be identified (North, 1994). Generally, institutions need to be adjusted, or "aligned", to a new technology, if it is to diffuse (Freeman and Louçã, 2002). Institutional alignment is, however, not an automatic and certain process but rather the opposite. Firms compete not only in the market but also

[17] Patent analysis is, however, far from unproblematic. The link between patent classes and products is unreliable (Bergek et al., 2004) and a patent analysis is probably more useful if we choose a knowledge field as the starting point. Yet even here, we cannot conclude that a firm with patents in a particular class necessarily masters a technology generally associated with that class. For instance, Holmén and Jacobsson (2000) carefully scrutinized patents referring to microwave antennas and found that some patents certainly did not reveal any deep knowledge in the knowledge field in question.

[18] "Mobile data" are here defined as non-voice communications, where at least one terminal is connected to the system via radio, providing mobility to the user. It is thus a generic technology which can be used in a large number of applications, ranging from e.g. simple SMS to advanced logistics applications.

over the nature of the institutional set-up (Davies, 1996; Jacobsson and Lauber, 2006; Van de Ven, 1993).

Institutions may come in a variety of forms and may influence the TIS in different ways. For example, in the case of the emerging TIS "IT in home care", a key institution is the procurement policies of the county councils, which discriminate against smaller suppliers. In the case of "biocomposites", the emerging TIS is influenced by a number of EU regulations and directives concerning broad areas such as chemical substances and recycling. This implies that analysts need to have a broad perspective when mapping relevant institutions.[19] Sometimes it is the very lack of institutions that is of interest. Again, in the case of the emerging TIS "IT in homecare", a lack of standardization has led to fragmented markets and poor incentives for firms to innovate.

For TISs that are only just emerging there are inherent uncertainties, implying that the identification of structural components is thorny and many of the sources mentioned above may be difficult to use. It may prove hard to recognize the relevant actors when directories are scarce, no industry associations exist or if the actors themselves are not aware of belonging to a certain TIS. This was the case for early studies of the emerging system for biomaterials (Rickne, 2000) and is, of course, an ever bigger problem in cases where the TIS concept is only an analytical tool for the researcher. Moreover, in early phases networks are usually undeveloped and/or informal and TIS-specific institutions may not yet exist. In instances like this, the structural mapping must be an iterative process, in which additional pieces of information are added as the analysis proceeds.

Identifying the structural components of the system provides a basis for the following step, which constitutes the core of the analysis: analyzing the TIS in functional terms.

6. Step 3: mapping the functional pattern of the TIS

The first step of a TIS analysis in functional terms is to describe the "functional pattern" of the TIS. This analysis aims at ascertaining to what extent the functions are currently filled in that TIS, i.e. to analyze how the TIS is behaving in terms of a set of key processes. This step has no normative features; assessing the "goodness" of the current functional pattern will be dealt with later in the paper. The functional pattern of a TIS is likely to differ from that of other TISs and is also likely to change over time. Thus, the concept should not be interpreted as implying that the pattern is either repeated or optimal.

In the following, we will explain each of these functions. As described above, they have been synthesized from a number of different system approaches to innovation and have been applied and further developed by ourselves and other researchers. We begin by explaining the content of the function. We will then give a brief illustrative example from various case studies that we have undertaken and examples of indicators that may reflect the extent to which the function is fulfilled. Of course, it is not possible to come up with an exact figure but the analyst has to make a composite judgment based on both qualitative and quantitative data. Exactly how that is done should be made explicit.

6.1. Knowledge development and diffusion

This is the function that is normally placed at the heart of a TIS in that it is concerned with the knowledge base of the TIS (globally) and how well the local TIS performs in terms of its knowledge base and, of course, its evolution. The function captures the breadth and depth of the current knowledge base of the TIS, and how that changes over time, including how that knowledge is diffused and combined in the system.

We can distinguish between different types of knowledge (e.g. scientific, technological, production, market, logistics and design knowledge) and between different sources of knowledge development, for example R&D (Bijker, 1995; Edquist and Johnson, 1997; Hughes, 1983; Nelson, 1992), learning from new applications, production, etc. (Bijker, 1995; Edquist and Johnson, 1997; Hughes, 1990; Lundvall, 1992b) and imitation (Edquist and Johnson, 1997; Nelson, 1992).[20]

An illustrative example is that of the emerging TIS for solar cells in Germany (Jacobsson et al., 2004). Initially, the type of knowledge development was limited to the scientific/technological field and the source was R&D on various competing designs for solar cells. The knowledge base was subsequently broadened as the system expanded along the entire value chain. First,

[19] Institutional factors may be even more distant from the focal TIS. Geels (2004) uses the concept of "technological landscapes", which influences many different TISs. Examples include the greenhouse effect discussion.

[20] It should be noted that part of this knowledge development takes place in the form of entrepreneurial experimentation. In the function 'entrepreneurial experimentation', however, we focus on the uncertainty reducing effects of these experiments rather than their results in terms of knowledge development.

application-specific knowledge was developed downstream as firms experimented with solar cells as a building element. Part of the knowledge development took place in schools of architecture where "solar architects" developed new design concepts. Second, upstream technological knowledge was enhanced through R&D performed by the capital goods industry. A significant aspect of that knowledge development was, however, also a very practical and problematic learning process to build automated production lines for the manufacturing of solar cells.

The current level and dynamics of the function could be measured by a range of indicators, including for instance bibliometrics (citations, volume of publications, orientation); number, size and orientation of R&D projects; number of professors; number of patents; assessments by managers and others; and learning curves.

6.2. Influence on the direction of search

If a TIS is to develop, a whole range of firms and other organizations have to choose to enter it. There must then be sufficient incentives and/or pressures for the organizations to be induced to do so. The second function is the combined strength of such factors. It also covers the mechanisms having an influence on the direction of search *within* the TIS, in terms of different competing technologies, applications, markets, business models, etc. These factors are not, of course, controlled by one organization – and definitely not by the state (apart from the case of regulations, etc.) – but their strength is the combined effect of, for example:

- visions, expectations (van Lente, 1993) and beliefs in growth potential:
  - incentives from changing factor and product prices (Dosi et al., 1990);
  - growth occurring in TISs in other countries;
  - changes in the "landscape" (Geels, 2004), e.g. demographic trends and climate change debates; and
  - development of complementary resources (Dahmén, 1988),
- actors' perceptions of the relevance of different types and sources of knowledge,[21]
- actors' assessments of the present and future technological opportunities and appropriability conditions (Breschi et al., 2000),
- regulations and policy (Lundvall, 1992b; Porter, 1990),
- articulation of demand from leading customers (e.g. Dosi et al., 1990; von Hippel, 1988; Carlsson and Jacobsson, 1993),
- technical bottlenecks or "reverse salients" (Rosenberg, 1976; Bijker, 1995; Hughes, 1983; Lundvall, 1992b), and
- crises in current business.

Wind turbines in Germany (in the early phase of system evolution) is an illustrative case in point, where firms experienced a range of incentives to enter the industry (Bergek and Jacobsson, 2003). In several cases, the firms' existing markets were in recession at the same time as there was a Californian wind turbine boom and an associated expansion of the Danish wind turbine industry. These latter developments gave clear signals about the attractiveness of the future wind turbine market (i.e. expectations of future markets). Locally, there was a "green" demand from some utilities and environmentally concerned farmers (articulation of demand). Federal R&D policy subsidized not only R&D in many competing designs but also investment in wind turbines in a number of demonstration programs (regulation).

We suggest that this function can be measured, or at least indicated, by qualitative factors of the following types:

- beliefs in growth potential,
- incentives from factor/product prices, e.g. taxes and prices in the energy sector,
- the extent of regulatory pressures, e.g. regulations on minimum level of adoption ("green" electricity certificates, etc.) and tax regimes, and
- the articulation of interest by leading customers.

6.3. Entrepreneurial experimentation

A TIS evolves under considerable uncertainty in terms of technologies, applications and markets. This uncertainty is a fundamental feature of technological and industrial development and is not limited to early phases in the evolution of a TIS but is a characteristic of later phases as well (Rosenberg, 1996). From a social perspective, the main source of uncertainty reduction is entrepreneurial experimentation, which implies a probing into new technologies and applications, where many will fail, some will succeed and a social learning process

[21] For example, actors are more likely to look for new knowledge within their current technological frame (McLoughlin et al., 2000) or paradigm (Dosi, 1982).

will unfold (Kemp et al., 1998).[22] A TIS without vibrant experimentation will stagnate.

An analyst needs to map the number and variety of experiments taking place in terms of, for example:

- number of new entrants, including diversifying established firms,
- number of different types of applications, and
- the breadth of technologies used and the character of the complementary technologies employed.

To continue with the German wind turbine case in the early phase of its evolution, it is clear that the diversity in experiments undertaken was its main characteristic (Bergek and Jacobsson, 2003). In the period 1977–1991, a large number of industrial firms and a range of academic organizations received federal R&D funding for the development or testing of a variety of turbine sizes and designs. As a result of some of these experiments, at least 14 firms entered wind turbine production, including academic spin-offs, diversifying medium-sized mechanical engineering firms and large aerospace firms, all of which brought different knowledge and perspectives into the industry.

6.4. Market formation

For an emerging TIS, or one in a period of transformation, markets may not exist, or be greatly underdeveloped (Carlsson and Stankiewicz, 1995; Dahmén, 1988; Galli and Teubal, 1997; Nelson, 1992; Porter, 1990). Market places may not exist, potential customers may not have articulated their demand, or have the capability to do so, price/performance of the new technology may be poor, and uncertainties may prevail in many dimensions. Institutional change, e.g. the formation of standards, is often a prerequisite for markets to evolve (Hughes, 1983).

Market formation normally goes through three phases with quite distinct features. In the very early phase, "nursing markets" need to evolve (Erickson and Maitland, 1989) so that a "learning space" is opened up, in which the TIS can find a place to form (Kemp et al., 1998). The size of the market is often very limited. This nursing market may give way to a "bridging market" (Andersson and Jacobsson, 2000), which allows for volumes to increase and for an enlargement in the TIS in terms of number of actors. Finally, in a successful TIS, mass markets (in terms of volume) may evolve, often several decades after the formation of the initial market.

To understand the sequence of the *formation* of markets, we need to analyze both actual market development and what drives market formation. The timing, size and type of markets that have actually formed, are normally quite easy to measure. For example, we could describe a market for wind turbines in terms of the number of turbines and/or the wind power capacity installed in a particular year and in terms of the distribution between different customer groups (e.g. farmers and energy companies).

It is more difficult to analyze what drives that formation, and the analyst needs to have in-depth knowledge of the TIS to do so. We will illustrate the multitude of factors that may drive or hinder market formation with the case of the Swedish "mobile data" TIS (see Lindmark and Rickne, 2005). In this case, markets are often global, but the home market is still strategically important to test new concepts and products, to learn, and to obtain early revenues. Swift market formation is, therefore, of essence to any national TIS. However, in the Swedish market, corporate and governmental use is slow. Sluggish procurement procedures and unarticulated demand cause great uncertainty about current or future user needs. In addition, Sweden lags behind countries such as Japan and Korea with regard to the dominant consumer market. Indeed, as of 2006 Sweden had a low rate of adoption of mobile data services, much due to unwillingness of operators to cannibalize current cash cows within mobile telecommunication, inflexible pricing systems, lack of standards for platforms, problems with complementary technologies and proprietary solutions.

The analyst needs to assess what phase the market is in (nursing, bridging, mature), who the users are and what their purchasing processes look like, whether the demand profile has been clearly articulated and by whom, if there are institutional stimuli for market formation or if institutional change is needed. Indicators to trace these developments include readily available facts (as indicated above) on market size and customer groups as representing what has been achieved, but also qualitative data on e.g. actors' strategies, the role of standards and purchasing processes.

6.5. Legitimation

Legitimacy is a matter of social acceptance and compliance with relevant institutions: the new technology

[22] It should be noted the word "entrepreneurial" does not refer only to new or small firms, but to the more general Schumpeterian notion of an "entrepreneurial function" (i.e. making new combinations). This function may be filled by any type of actor, including large, established firms diversifying into the new technology.

and its proponents need to be considered appropriate and desirable by relevant actors in order for resources to be mobilized, for demand to form and for actors in the new TIS to acquire political strength. Legitimacy also influences expectations among managers and, by implication, their strategy (and thus the function 'influence on the direction of search').

As is widely acknowledged in organization theory, legitimacy is a prerequisite for the formation of new industries (Rao, 2004) and, we would add, new TISs (cf. Bijker, 1995; Carlsson and Stankiewicz, 1995; Edquist and Johnson, 1997; Hughes, 1983). Legitimacy is not given, however, but is formed through conscious actions by various organizations and individuals in a dynamic process of *legitimation*, which eventually may help the new TIS to overcome its "liability of newness" (Zimmerman and Zeitz, 2002). However, this process may take considerable time and is often complicated by competition from adversaries defending existing TISs and the institutional frameworks associated with them.

Although the process of legitimation is often closely associated with institutional alignment, "manipulation" of the rules of the game is only one of several possible alternative legitimation strategies; other alternatives include "conformance" (following the rules of the existing institutional framework, e.g. choosing to follow an established product standard) and "creation" (developing a new institutional framework) (Suchman, 1995; Zimmerman and Zeitz, 2002). With respect to the latter, however, a new TIS seldom emerges in a vacuum, but instead is often subjected to competition from one or more established TIS. In such cases, some type of manipulation strategy is usually needed.

Mapping the functional dynamics of 'legitimation' includes analyzing both the legitimacy of the TIS in the eyes of various relevant actors and stakeholders (not least the ones that could be expected to engage in the development of the new technology, e.g. potential capital goods suppliers and buyers), and the activities within the system that may increase this legitimacy. So, we need to understand:

- the strength of the legitimacy of the TIS, in particular whether there is alignment between the TIS and current legislation and the value base in industry and society;
- how legitimacy influences demand, legislation and firm behavior; and
- what (or who) influences legitimacy, and how.

An interesting illustration of the process of legitimation is provided by the case of solar cells in Germany (see Jacobsson and Lauber, 2006). After unsuccessful efforts to convince the federal government to launch a nationwide regulatory change in favor of the diffusion of solar cells in the early 1990s, a number of activists and interest organizations began lobbying work at the Länder and local levels. After much effort, most Länder expressly allowed cost-covering contracts between suppliers of (very expensive) solar power and local utilities. Several dozen cities subsequently opted for this model, which revealed a wide public interest in increasing the rate of diffusion – the legitimacy of solar power was made apparent. Various organizations could later point to this interest when they lobbied for a program to develop yet larger markets for solar cells, now at the federal level.

6.6. Resource mobilization

As a TIS evolves, a range of different resources needs to be mobilized (Carlsson and Stankiewicz, 1995; Dahmén, 1988; Edquist and Johnson, 1997; Hughes, 1983; Lundvall, 1992b; Nelson, 1992; Porter, 1990; Rickne, 2000). Hence, we need to understand the extent to which the TIS is able to mobilize *competence/human capital* through education in specific scientific and technological fields as well as in entrepreneurship, management and finance, *financial capital* (seed and venture capital, diversifying firms, etc.), and *complementary assets* such as complementary products, services, network infrastructure, etc.[23]

As an illustration of this function, we will use a recent analysis of the Swedish security sensor TIS (Oltander and Perez Vico, 2005). The mobilization of human resources was found to be strong, partly following a recent reduction of personnel at the Swedish telecommunication company Ericsson. However, in specific knowledge fields, such as radar and sonar technology, there was a resource shortage, explained by an absence of university education in these fields. The mobilization of financial resources was more troublesome. In addition to a generally weak Swedish seed capital market, there were also difficulties in attracting venture capital, resulting from (a) a cautious VC market in general, and (b) a belief that Swedish start-ups will have problems competing internationally with US firms. In larger organizations (e.g. Saab Bofors Dynamics and Ericsson Microwave) there were some perceived difficulties in raising funding for internal R&D projects, because of an

[23] Here, we follow the reviewed literature on innovation systems, where resource mobilization is treated as a process separate from the other functions.

absence of strong customers and the ongoing transition from military to civilian markets.

There are thus various ways for analysts to measure resource mobilization:

- rising volume of capital,
- increasing volume of seed and venture capital,
- changing volume and quality of human resources (e.g. number of university degrees), and
- changes in complementary assets.

In the analysis referred to above, Oltander and Perez Vico (2005) used quantitative measures, such as the number of graduates from sensor-related education (absolute and per capita) in comparison to Germany and Israel and the number of venture capital firms with holdings in the security sensor sector, together with qualitative data based on interviews, such as perceptions about the supply of human resources and the VC firms' interest in the Swedish security sensor sector.

6.7. Development of positive externalities

The systemic nature of the innovation and diffusion process strongly suggests that the generation of positive external economies is a key process in the formation and growth of a TIS.[24] These external economies, or free utilities, may be both pecuniary and non-pecuniary (Scitovsky, 1954).

Entry of new firms into the emerging TIS is central to the development of positive externalities. First, new entrants may resolve at least some of the initial uncertainties with respect to technologies and markets (Lieberman and Montgomery, 1988), thereby strengthening the functions 'influence on the direction of search' and 'market formation'. Second, they may, by their very entry, legitimate the new TIS (Carroll, 1997). New entrants may also strengthen the political power of advocacy coalitions that, in turn, enhance the opportunities for a successful legitimation process. An improved legitimacy may, in turn, positively influence changes in four functions: 'resource mobilization', 'influence on the direction of search', 'market formation' and 'entrepreneurial experimentation'. Third, the greater the number and variety of actors in the system, the greater are the chances for new combinations to arise, often in a way which is unpredictable (Carlsson, 2003). An enlargement of the actor base in the TIS therefore enhances not only the opportunities for each participating firm in the system to contribute to 'knowledge development and diffusion' but also for the firms to participate in 'entrepreneurial experimentation'.

Hence, new entrants may contribute to a process whereby the functional dynamics of the TIS are strengthened, benefiting other members of the TIS through the generation of positive externalities. This function is thus not independent but works through strengthening the other six functions. It may, therefore, be seen as an indicator of the overall dynamics of the system.[25]

These dynamics may be enhanced by the co-location of firms. Marshall (1920) discussed economies that were external to firms but internal to location, and outlined three sources of such economies:

- *Emergence of pooled labor markets*, which strengthen the 'knowledge development and diffusion' function, in that subsequent entrants can access the knowledge of early entrants by recruiting their staff (and vice versa as time goes by).
- *Emergence of specialized intermediate goods and service providers*; as a division of labor unfolds, costs are reduced and further 'knowledge development and diffusion' is stimulated by specialization and accumulated experience.[26]
- *Information flows and knowledge spill-overs*, contributing to the dynamics of 'knowledge development and diffusion'.

In sum, the analyst needs to capture the strength of these functional dynamics by searching for external economies in the form of resolution of uncertainties, political power, legitimacy, combinatorial opportunities, pooled labor markets, specialized intermediates, as well as information and knowledge flows.

To refer again to the German wind turbine case, we will mention two forms of positive externalities. First, new entrants into the wind turbine industry, as well as into wind power production, increased the political power of the advocates of wind energy so that they could win against opposing utilities in several courts and defend a favorable institutional framework (Jacobsson and Lauber, 2006). Second, as the market increased, spe-

[24] See in particular Marshall (1920) and Porter (1990).

[25] We are grateful to Professors Ruud Smits and Marko Hekkert on this point. The dynamics are, of course, enhanced by the interdependencies of the functions, as was pointed out above. As the system moves into a growth phase characterized by positive feedback loops, these interdependencies are clearly seen.

[26] See Smith (1776), Young (1928), Stigler (1947), Rosenberg (1976), and Maskell (2001). For a case study of mobile data in Western Sweden, see Holmén (2001).

cialized suppliers emerged, with the consequence that barriers to entry for yet more firms were lowered (Bergek and Jacobsson, 2003).

7. Step 4: assessing the functionality of the TIS and setting process goals

The analyst now has a description of the dynamics of these seven key processes, or functions, in the evolution of a TIS, as well as a tentative assessment of the strengths and weaknesses of these processes. However, the functional pattern does not in itself tell us whether the TIS is well functioning or not; that a particular function is weak does not always constitute a problem, nor is a strong function always an important asset. In order to assess system functionality – i.e. not *how*, but *how well* the system is functioning – we need ways to evaluate the relative "goodness" of a particular functional pattern. This is, of course, the same problem as we alluded to in Section 2.2, i.e. evaluating the "goodness" of a particular structure. The advantage with a functional analysis is that we can systematically address the issue of "goodness" in terms of the seven clearly specified key processes.

Although this is a step forward, we face here one of the major challenges for analysts and policy makers, a challenge that needs to be dealt with further in research and in learning processes among practitioners. So far, we have identified two bases for an assessment: (1) the phase of development of the TIS, and (2) system comparisons. Both are associated with different types of problem and in order to balance each other's weaknesses, they should probably be used in combination.

7.1. The phase of development

We have earlier suggested that it is useful to distinguish between a formative phase and a growth phase in the development of a TIS and that it is plausible that the definition of "functionality" differs between these phases (Bergek and Jacobsson, 2003; Jacobsson and Bergek, 2004). The analyst can then raise the question whether functionality matches the needs of that particular phase or the need of the next phase (if it is judged to be desirable that the TIS is to move in that direction). In other words, the functional pattern, i.e. how the functions, or key processes, are performed and improved, can be analyzed with respect to the requirements of each phase.

Although it is not always a straightforward exercise, the analyst can use a number of indicators to know whether or not a TIS is in a formative phase. In this phase the constituent elements of the new TIS begin to be put into place, involving entry of some firms and other organizations, the beginning of an institutional alignment and formation of networks. A rudimentary structure is formed. Apart from exhibiting rudimentary structural components, the formative phase may be indicated by, for instance:

- the time dimension, where we rarely escape formative periods that are shorter than a decade (yet they can last for many decades, as in the case of solar cells);
- large uncertainties prevailing as regards technologies, markets and applications;
- price/performance of the products being not well developed;
- a volume of diffusion and economic activities that is but a fraction of the estimated potential;
- demand being unarticulated; and
- absence of powerful self-reinforcing features (positive feedbacks) and weak positive externalities.

A common error made by analysts is to judge a TIS that is in a formative phase by using criteria that are more suitable for evaluating a system which is in a growth phase. For example, the formative phase is *not* characterized by a rapid rate of diffusion or rapid growth in economic activities. On the contrary, the volume of activities is small and many experiments take place – the TIS is in a process of formation. Yet, in several cases we know of – renewable energy technologies and wood manufacturing, for instance – emerging TISs were evaluated, by policy makers and others, by the volume (level) of economic activities. Of course, this led to a great deal of frustration and a feeling of disappointment and failure. By applying other criteria, more suited for a formative phase, a quite different interpretation would be made.

In particular, the formative phase is characterized by high uncertainty in terms of technologies and markets (Kemp et al., 1998; Van de Ven, 1993), and the key words are therefore experimentation and variety creation. This requires extensive 'entrepreneurial experimentation' in such a way that 'knowledge development' occurs within a number of different technological approaches and applications. For this to take place, 'influence on the direction of search' and 'resource mobilization' must stimulate not only entry of firms but also ventures embarked upon in many directions. Moreover, a process of 'legitimation' must start, helping to overcome the "liability of newness" associated with new actors and technologies and eventually leading to institutional change. Finally, 'knowledge development' is to a large extent dependent on cooperation between actors (in networks), especially between suppliers and buyers, which require 'market formation'. Thus, either established markets need to be open to new technologies/products, or new niches need to be identified and stimulated.

At some point in time, the TIS may be able to "change gear" and begin to develop in a self-sustaining way as it moves into a *growth phase*. In this phase, the focus shifts to system expansion and large-scale technology diffusion through the formation of bridging markets and subsequently mass markets; hence the need for 'resource mobilization' increases by orders of magnitude. Yet, it is normally not self-evident which applications will generate such markets, so a breadth of 'entrepreneurial experimentation' must be kept up. As and when the growing TIS catches the attention of actors in competing TISs, 'legitimation' may become even more important.

Although the phase thus presumably matters for how we assess functionality, we want to emphasize that this does not imply that all TISs follow exactly the same development pattern. Indeed, the whole point of the functional dynamics approach is that TISs differ so much that there are no "one size fits all" policy implications. Hence, although some features in TIS development are arguably common to many innovation systems, we fully acknowledge that the determining factors, time frames, etc., differ between cases. We also acknowledge that more research is needed to establish the nature of the different phases. This implies that we must be careful not to specify a "desired" functional pattern too rigidly, and need to be open for reformulation and iteration in the process of analysis.

7.2. Comparisons between TISs

Comparing the focal TIS with other TISs, across regions or nations, is a powerful way of improving the understanding for decision makers (see e.g. Rickne (2000) for biomaterials in Sweden, Massachusetts and Ohio, and Bergek and Jacobsson (2003) for wind turbines in Sweden, the Netherlands and Germany). Researchers and policy makers involved with a particular innovation system thus ought to perform analyses of similar systems being developed elsewhere or of systems in related areas. Most importantly, they need to address the question of how these other systems are performing in order to gauge correctly not only what development it is reasonable to expect of their focal TIS but also in identifying the critical functions. For instance, in our earlier work on the TIS centered on wind turbines (Bergek and Jacobsson, 2003), Dutch researchers pointed to weak market formation in the Netherlands as an explanation of the perceived unsatisfactory development of the TIS. Yet, in its formative phase, the Dutch home market was larger (even in absolute terms) than the German and much larger than the Swedish one. A search for an explanation would then shift to how an initially favorable position was not leveraged to propel the system into a growth phase ahead of the competing German TIS.

Based on the phase analysis and/or one or more comparative analyses, a tentative conclusion regarding functionality of the TIS may be drawn, that is, in relation to what it is reasonable to expect taking the phase of development and/or the comparison with other systems into consideration. It is then also possible to specify policy goals in terms of how the functional pattern should develop in order to reach higher functionality, i.e. towards a "targeted" functional pattern. Such goals (e.g. broaden the knowledge base or widen the range of experiments) can be seen as *process goals*. Hence, policy goals may be expressed in terms of the seven key processes in contrast to final goals (such as growth). Process goals have the advantage for policy makers in that they are "closer" to the various instruments that can be used, and they also make it easier to evaluate how well a specific policy works. In particular, in early phases of development final goals may be close to impossible to define, since the uncertainty regarding what the TIS may be able to achieve in the long term, also regarding and what it is desirable to achieve, is very high.

8. Step 5: identify inducement and blocking mechanisms

There are many reasons for expecting that the environment is biased, and will remain biased, in favor of established TISs.[27] New TISs may consequently exhibit weak functional dynamics and develop slowly, or in a stunted way. The functional dynamics may be weak for a number of reasons. These may be found in features of the structural components of the emerging TIS and in the larger context surrounding it.[28] This larger context includes the sector in which the new TIS operates, e.g. the electric power sector for the emerging TIS centered on solar cells, but also factors that go beyond that sector. For instance, the reaction, or lack of it, to global warming

[27] Jacobsson and Johnson (2000) and Johnson and Jacobsson (2001) elaborate on various types of "blocking mechanisms". See also Unruh (2000) for an extensive review of mechanisms locking us into a carbon economy and Walker (2000) for a case study on entrapment in a large technological innovation system.

[28] See e.g. Geels (2004), who distinguishes between "regime" and "landscape" levels, where "regime" is broadly equivalent to the sector.

acts either as an inducement mechanism[29] or as a blocking mechanism in many sectors, and this influences many emerging TISs.

What is being achieved in the TIS is therefore only in part a result of the internal dynamics of the TIS. Exogenous factors also come into play, influencing the internal dynamics. Myrdal (1957, p. 18) showed a keen understanding of the interplay between internal and external sources of dynamics and even suggested that "the main scientific task is . . . to analyze the causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its own internal processes".

From a policy perspective, it is particularly important to understand the blocking mechanisms that shape the nature of the dynamics. These could, for instance, be of the following types:

- The proponents of the new technology may be organizationally too weak to contribute to a 'legitimation' process; they may, for example, lose in a "battle over institutions" as they attempt to achieve institutional alignment to the new technology. Unaligned institutions may then lead to poor 'market formation' that, in turn, limits the strength of the 'influence on the direction of search' and 'entrepreneurial experimentation' functions.
- Underdeveloped capabilities among potential customers may lead to an absence, or poor articulation, of demand which results in a poor development of the dynamics of 'market formation', 'influence on the direction of search' and 'entrepreneurial experimentation'.
- Networks may fail to aid new technology simply because of poor connectivity between actors. Tight networks may also through a "lock-in" effect have an 'influence on the direction of search' among potential suppliers and customers away from the new TIS.

As is evident from these examples, there may be quite different things that block the development of functions. The path to achieving a higher functionality may, therefore, be littered by a range of such blocking mechanisms. These may operate in a formative stage, but they may also obstruct a transition towards a more self-sustained TIS, i.e. one which is to an increasing extent driven by its own momentum rather than by outside pushes or pulls in the form of policy.

It is empirically possible, and very useful, to map the relationship between inducement/blocking mechanisms and functional patterns. We will illustrate this with the example of the emerging TIS for "IT in home care", which, as was noted above, is defined by the application of a generic technology (IT) to a particular application: care of elderly and ill people in their homes instead of in a hospital. For a number of reasons (demographic, public sector funding restrictions, technological opportunities, etc.), this is a TIS which is thought of as having a large growth potential.[30] However, it is still in a formative phase, as judged by, for instance, the following features:

- There are no software standards and the technical uncertainty is high.
- The number of firms supplying IT solutions is small.
- Markets are small, and characterized by high uncertainty, e.g. with respect to applications and choice of software.
- The advocacy coalition for the TIS is weak.
- The demand is poorly articulated by customers with poorly developed capabilities.

In this formative phase, the functional pattern can be summarized as follows:

- 'Knowledge development and diffusion': pilot projects in some of the 290 counties and 21 county councils,
- 'Market formation': local pilot projects constitute "nursing markets", albeit fragmented,
- 'Influence on the direction of search': government R&D funding, opportunities to find new markets, awards,
- 'Entrepreneurial experimentation': a few IT firms have developed solutions,
- 'Resource mobilization': EU and government R&D funding, some co-funding by firms, poor adjustment by the higher educational sector,
- 'Legitimation': partly underdeveloped legitimacy, especially among care providers, and
- 'Development of positive externalities': early stage of cluster formation in three cities.[31]

[29] A case in point is the transnational legislation concerning tradable emission permits which may influence investment decisions in many TISs.

[30] This is the judgment of VINNOVA (the Swedish Agency for Innovation Systems).

[31] Since we have not been able to determine how this function influences the other functions, we will not include it in the following discussion.

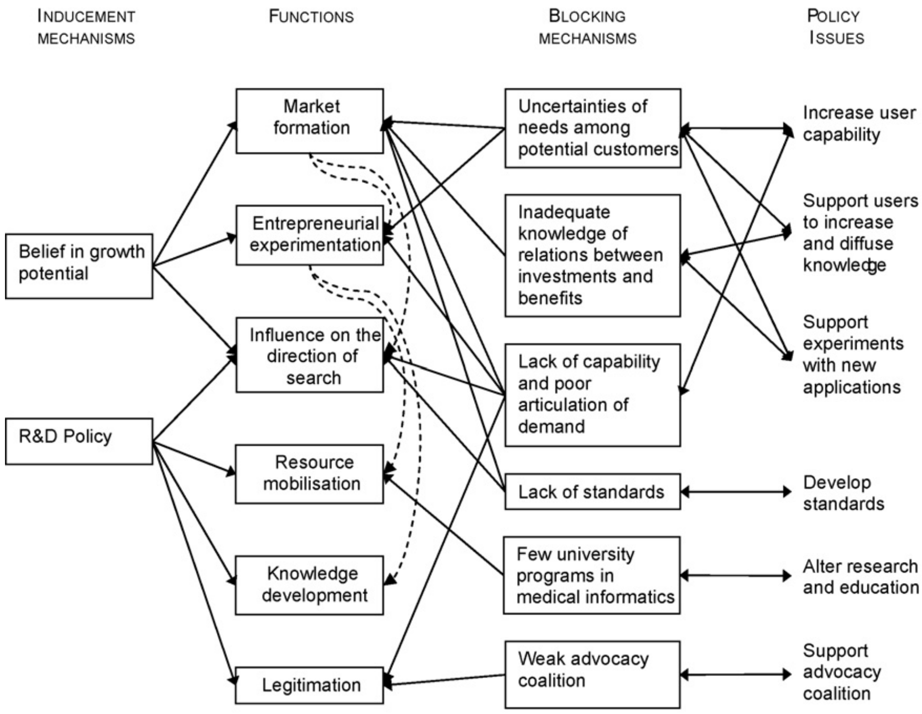

Fig. 2. Inducement and blocking mechanisms as well as policy issues in the case of "IT in home care". *N.B.*: The function "Development of positive externalities" has been excluded from the discussion (see footnote 30).

The current functional pattern is shaped by both inducement and blocking mechanisms (see Fig. 2). There are two significant *inducement* mechanisms: a belief in growth potential and government R&D policy. The former is driven by a range of factors, as was mentioned above.[32] This inducement mechanism has a bearing on the function 'influence on the direction of search' among both care providers (e.g. county councils) and suppliers (IT firms), as well as on the dynamics of 'market formation' (nursing markets) and 'entrepreneurial experimentation'. The latter inducement mechanism both signals attractiveness and provides resources for research and experiments. Hence, it strengthens the functional dynamics of 'influence on the direction of search' and 'legitimation', as well as 'resource mobilization' and 'knowledge development and diffusion'.[33]

The *blocking* mechanisms are, however, strong and manifold. 'Market formation' is blocked by an absence of standards (which leads to a fragmented market), two factors that reflect poor awareness and capabilities among potential customers (leading to poor articulation of demand) and an associated lack of knowledge among suppliers of IT solutions of customer needs. Additionally, 'entrepreneurial experimentation', 'influence on the direction of search' and 'legitimation', are each blocked by two factors. These three have a common blocking mechanism in the form of a lack of capability and a poor articulation of demand. This is strengthened by an additional but different factor in each case (uncertainties of customer needs, lack of standard software solutions and a weak advocacy coalition).

Some mechanisms block several functions. In particular, a poor articulation of demand (due to lack of capability) blocks not only the three functions mentioned above but also 'market formation'. Moreover, functions are not independent, but rather tend to reinforce one another. A poor 'market formation' affects negatively both 'entrepreneurial experimentation' and 'influence on the direction of search', whereas little 'entrepreneurial experimentation' negatively influences 'resource mobilization' and 'knowledge development and diffusion'. This means that the impact of blocking mechanisms is magnified by such interdependencies. Clearly, it could be argued that policy must focus on reducing the strength of the blocking mechanisms that have such a pervasive effect.

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[32] These include demographic changes with a larger share of elderly people in the population, public sector funding restrictions and emerging technological opportunities.

[33] Indirectly, it also strengthens 'entrepreneurial experimentation' as a consequence of its positive influence on the direction of search.

9. Step 6: specify key policy issues

Process goals were defined in the fourth step above. Having made explicit both the reasons for setting these specific process goals and how to measure whether the goals are reached, we can now begin to specify the key policy issues related to the mechanisms that block or induce a development of a desirable functional pattern. We argue that policy should aim at remedying poor functionality in relevant TISs by strengthening/adding inducement mechanisms and weakening/removing blocking mechanisms. In doing so, we take a step away from the traditional "market failure" rationale for policy interventions into innovation processes and focus on "system failure" in terms of functional weaknesses rather than structural deficiencies.

We will continue to use "IT in home care" as an illustrative case and refer to the fourth column in Fig. 2, where we list six specific policy issues connected to removing or reducing the strength of the many blocking mechanisms. The first three of these focus on the potential customers (care providers) and are aimed at removing the most pervasive blocking mechanisms:

- how to raise user capability so that demand is articulated and uncertainties reduced for potential suppliers;
- how to support users in order to (a) increase their knowledge of the benefits of IT in home care and of ways to distribute the costs and benefits over organizational boundaries and (b) diffuse knowledge of the outcome of early experiments in order to reduce uncertainties further; and
- how to support experimentation with new applications in order to reduce the level of uncertainty of needs.

In addition to these three issues, we can also deduce three additional ones, relating to one blocking mechanism each:

- how to develop standards in order to move from a fragmented market of 290 local councils and 21 county councils;
- how to alter research and education at universities in order to allow for 'resource mobilization' in terms of staff with relevant background; and
- how to support a weak advocacy coalition so that it can improve the process of 'legitimation'.

Hence, by analyzing weaknesses in the functional pattern of the TIS (i.e. "what is actually going on"), we can identify the key blocking mechanisms that, in turn, lead us to a specification of the relevant policy issues.

10. Summary and discussion

The objective of this paper has been to make the innovation system approach more useful to innovation system researchers and policy makers by presenting a practical scheme of analysis that can be used to identify the key policy issues and set goals in any given TIS. We have outlined six "steps" in such a scheme. The core of this operationalization of the innovation system perspective referred to the description and evaluation of seven *key processes,* here labeled *functions*, in the evolution of a TIS. The main benefit of this framework is that it focuses on what is actually achieved in the system, rather than on the structure of the system (the goodness of which is difficult to evaluate without referring in a systematic way to these processes).

The main application of the framework is the identification of "system failures" or weaknesses, expressed in functional terms. Policy makers can also define process goals of their intervention in terms of an altered functional pattern, i.e. an altered way in which the seven key processes are operating. By explaining the nature of these processes in terms of the outcome of a balance between various inducement and blocking mechanisms, the functional dynamics approach can then be used as a focusing device for policy makers that seek to identify the key policy challenges for moving a specific TIS towards these process goals.[34] As the functions approach includes a systematic mapping of a larger number of key processes than in most previous research, its use implies that a wider range of possible policy challenges may be identified. In consequence, the functions approach further strengthens the tendency of an innovation system perspective to open up richer

[34] Here we need to remind ourselves of what Charles E. Lindblom wrote many years ago: "[p]olicy-making is a process of successive approximation to some desired objectives in which what is desired itself continues to change under reconsideration . . . Making policy is at best a very rough process. Neither social scientists, nor politicians, nor public administrators yet know enough about the social world to avoid repeated error in predicting the consequences of policy moves. A wise policy-maker consequently expects that his policies will achieve only part of what he hopes and at the same time will produce unanticipated consequences he would have preferred to avoid. If he proceeds through a *succession* of incremental changes, he avoids serious lasting mistakes in several ways" (Lindblom, 1959, p. 86). See also Smits and Kuhlmann (2002) on this point.

and more difficult innovation policies (Bergek et al., 2007b).[35]

In the course of this scheme of analysis, we have emphasized the many sources of uncertainties, not only those that are inherent in the process of industrial development but also those additional sources facing the analyst in search of useful methods and tools. We are still at an early stage in our understanding of how TISs emerge and develop and we need to learn a lot more about methods such as indicators and, most importantly, about how to assess functionality. In relation to the latter issue, three points can be made.

First, there is, indeed, a need for more research on how to assess TIS functionality, i.e. the "goodness" of different functional patterns. In this paper, we have presented two ways forward: assessment based on the requirements of particular phases of development and assessment based on comparisons between systems. It would, however, be of benefit for the area of innovation system analysis if generally applicable assessment models could be developed.

Second, a promising way forward towards this aim seems to be an assessment based on the phase of development of the system. In particular, we need to better understand the formative phase and establish to what extent, and in what ways, the functional requirements of that phase differ from those of later phases. Although we acknowledge that systems are different and develop in different ways, we do not think that the variation is infinite. It ought to be possible – and fruitful – to develop a taxonomy of "archetypal" development paths with associated functional patterns by empirical investigation.

Third, such taxonomy may also be needed in order to better inform policy makers under what conditions a transition between the formative phase and a growth phase may occur and how the foundation for such a transition can be laid. A transition would involve leveraging the investment made in the formative phase by inducing a "change of gear" in the development of the TIS. As shown in the case of wind power in the Netherlands and solar heating in Sweden, a successful formative phase does not necessarily lead to a successful growth phase (Jacobsson and Bergek, 2004).

Finally, a scheme of analysis of this kind builds on present knowledge and it is therefore by no means a finished product. Only by a systematic learning process can we improve our understanding of the opportunities and limitations of innovation system analysis and policy making. Therefore, we expect further empirical studies – in combination with the research outlined above – to induce several revisions of the framework in the future.

[35] It also allows for comparisons between different TISs, which are based not on structural characteristics but on the underlying mechanisms of the innovation process and their changes in each system.

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Appendix A. Matching functions in the literature[36]

As far as we know, there have been nine attempts to identify functions that need to be filled for an innovation system to evolve and perform well: Galli and Teubal (1997), Johnson (1998), Johnson (2001), Rickne (2000), Johnson and Jacobsson (2001), Bergek (2002), Bergek and Jacobsson (2003), Carlsson et al. (2005), Liu and White (2001), and Hekkert et al. (2007). In addition, Edquist (2004) lists a number of "activities", defined as "those factors that influence the development, diffusion, and use of innovation" (p. 190), which is based on a similar comparison as ours.

In the table below, we have matched the functions suggested by these authors, excluding Liu and White (2001) since their framework is included in Edquist's (2004) synthesis.[37] Most of these original functions are formulated as verbs, in contrast to the functions in this paper, which are formulated as nouns. This reflects a conscious choice on our part; as described above we want to emphasise the process nature of the functions and remove any notion of a particular actor filling them. From the table, we can make the following observations.

First, three of the functions are more or less identical in all lists: 'supply resources', 'create knowledge' and 'stimulate/create market' (except for Galli and Teubal, 1997), although the authors differ in the degree of

[36] This section is based on Bergek et al. (2005).

[37] We have also excluded one of the functions identified by Galli and Teubal (1997) – "policy-making" – since it refers to the activities by one particular type of actor (i.e. policy makers) and can be directed towards all functions.

detail provided for each function.[38] In this paper, these functions are labeled 'knowledge development and diffusion', 'resource mobilization', and 'market formation', respectively.

Second, Bergek and Jacobsson's (various) function 'guide the direction of search' is an aggregate of four of Johnson/Bergek's (1998, 2001, 2002) functions (by design) and corresponds, at least in part, to Hekkert et al.'s (2007) 'articulation of demand' (which is much broader than the demand articulation that others include in 'market formation'), to Carlsson and Jacobsson's (2004) 'incentives' and to Rickne's (2000) 'direct technology, market and partner search'. Edquist's (2004) function 'creating or changing institutions that provide incentives or obstacles to innovation' is broader and applies also to another function in this paper (see below). In this paper, all these functions are gathered under the label 'influence on the direction of search'.

Third, Bergek and Jacobsson's (various) as well as Carlsson and Jacobsson's (2004) function 'promoting positive externalities' is much broader than Galli and Teubal's (1997), Johnson/Bergek's (1998, 2001, 2002), Rickne's (2000) and Hekkert et al.'s (2007), that focus on one source of external economies—diffusion of information/knowledge. Indeed, this function was developed a great deal in Jacobsson and Bergek (2004) and built yet further on in Carlsson and Jacobsson (2004). In this paper, we use the label 'development of external economies' for the broader concept. Knowledge diffusion is included in the function 'knowledge development and diffusion'.

Fourth, Johnson/Bergek's (1998, 2001, 2002) 'counteract resistance to change', which refers primarily to the extremely important process of legitimation, may be linked to Hekkert et al.'s (2007) 'development of advocacy coalitions', to Rickne's (2000) 'legitimize technology and firms', to Edquist's (2004) 'creating or changing institutions that provide incentives or obstacles to innovation', and to Galli and Teubal's (1997) 'design and implementation of institutions'. Carlsson and Jacobsson (2004) discuss this aspect under the heading of 'incentives', and Bergek and Jacobsson (various) included it into 'guide the direction of search'. We are, however, hesitant to include advocacy coalitions in a function, since they are a kind of network, i.e. a structural component. In this paper, this function is labeled 'legitimation'.

Finally, the function 'promoting entrepreneurial experiments' mentioned by Carlsson and Jacobsson (2004) is not explicitly mentioned by any of the other authors, with the exception of Edquist (2004) who includes "enhancing entrepreneurship" in his function 'creating and changing organizations needed'. In this paper, we use the label 'entrepreneurial experimentation' in order to emphasize that it is the creation of new combinations and variety that is in focus and that many different types of actors – not only new ones – may contribute to this function.

[38] For example, in Rickne (2000) the function 'supply resources' corresponds to four different functions.

This paper	Johnson (1998), Johnson (2001), and Bergek (2002)	Rickne (2000)	Bergek and Jacobsson (various)	Carlsson et al. (2005)	Edquist (2004)	Galli and Teubal (1997)	Hekkert et al. (2007)
Knowledge development and diffusion	Create knowledge, facilitate information and knowledge exchange	Create human capital	Create new knowledge	Creating a knowledge base	Provision of R&D, competence building	R&D diffusion of information, knowledge and technology	Creation of technological knowledge
Entrepreneurial experimentation	Create knowledge		Create knowledge	Promoting entrepreneurial experiments	Creating and changing organizations needed (e.g. enhancing entrepreneurship)		
Influence on the direction of search	Identify problems. Guide the direction of search. Provide incentives for entry. Recognise the potential for growth	Direct technology, market and partner search. Create and diffuse technological opportunities	Guide the direction of the search process	Creating incentives	Articulation of quality requirements (demand side). Creating/changing institutions that provide incentives or obstacles to innovation		Articulation of demand. Prioritizing of public and private sources (the process of selection)
Market formation	Stimulate market formation	Create market/diffuse market knowledge. Facilitate regulation (may enlarge market and enhance market access)	Facilitate the formation of markets	Creating markets or appropriate market conditions	Formation of new product markets. Articulation of quality requirements (demand side)		Regulation and formation of markets. Articulation of demand
Development of positive external economies	Facilitate information and knowledge exchange	Enhance networking	Facilitate the creation of positive external economies	Promoting positive externalities, or ‘free utilities’	Networking	Diffusion of information, knowledge and technology. Professional coordination	Exchange of information through networks
Legitimation	Counteract resistance to change	Legitimize technology and firms			Creating/changing institutions that provide incentives or obstacles to innovation	Design and implementation of institutions. Diffusion of scientific culture	Development of advocacy coalitions for processes of change
Resource mobilization	Supply resources	Facilitate financing. Create a labour market. Incubate to provide facilities, etc. Create and diffuse products (materials, parts, compl. products)	Supply resources	Creating resources (financial and human capital)	Financing of innovation processes, etc. Provision of consultancy services. Incubation activities	Supply of scientific and technical services	Supply of resources for innovation

Sources: Bergek (2002), Bergek and Jacobsson (various), Carlsson et al. (2005); Edquist (2004); Galli and Teubal (1997); Hekkert et al. (2007); Johnson (1998), Johnson (2001), Rickne (2000).

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