THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Capturing and explaining the effects of academic research and development

The case of nanotechnology

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Abstract

This thesis explores how the effects of academic research and development (R&D) can be captured and explained, and examines how these effects come about in the case of nanotechnology in Sweden. This includes the understanding of what obstructs the effects and how policy can reduce obstacles.

The research questions are explored in two papers. The first one suggests a systemic conceptualization for capturing and explaining the effects of academic R&D by enriching the technological innovation system (TIS) approach with a classification of activities sprung from academic R&D. A literature analysis underpins the conceptual framework and identifies a wide range of impacts. In particular, impacts on less tangible processes in a TIS, such as influence on the direction of search, legitimation and development of positive externalities are recognized.

The second paper is a case study on the nanotechnological innovation system in Sweden and utilizes the conceptualization as an analytical framework. A wide variety of academic R&D activities are identified, aimed at many functions, such as 'influencing the direction of search' of actors in the system, enhancing the 'legitimation' of the field, strengthening 'knowledge development and diffusion' as well as 'resource mobilisation' in terms of, e.g. human capital. However, the impact is constrained by, e.g., uncertainties regarding environmental and health effects, markets and institutions. Policy can reduce the strength of these mechanisms by supporting knowledge development on potential environmental and health risks, facilitating the formation of nursing markets and funding verification and scaling up of production.

The thesis raises methodological issues related to delineating the TIS for a generic technology or knowledge field, the sequence of conducting the study and overall reflections on the viability of the analytical framework. It also enables a more informed policy perception of the impact of academic R&D that takes the diversity of impacts, the influence from the surrounding environment and possible time lags into account. The importance of a concerned policy actor with a holistic competence transcending traditional policy boundaries is also stressed.

The thesis suggests further research to develop the conceptualization, to explore mismatches in policy tasks and policy regimes and to extend the analysis from dealing with impacts in terms of growth to also include the direction of a TIS.

Key words: Technological innovation systems, academic research, research evaluation, innovation and research policy, impact of research, nanotechnology.

Papers

Jacobsson, S., Perez Vico, E., 2010. Towards developing a systemic framework for capturing and explaining the effects of academic R&D, *Technology Analysis and Strategic Management*, to be published in October 2010.[1]

Perez Vico, E., Jacobsson, S., 2010. The influence of academic R&D on the commercialization of nanotechnology in Sweden, manuscript.

[1] The text of this paper will be slightly revised in the published version in response to comments from the copy editor. This refers particularly to the references.

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Contents

1. Introduction

This thesis is part of a larger research project on 'How to Trace, Measure and Explain the Societal Effects of Academic R&D' (Jacobsson and Lindholm Dahlstrand, 2007). Akin to the project, this thesis is placed into the debate on a perceived poor effect of academic research on economic development.[2] There is a dominant belief, in Sweden and Europe, that the results of academic research are insufficiently exploited (e.g. Dosi et al., 2006; European Commission, 2007; Jacobsson et al., 2010). In this debate, academic entrepreneurship, patenting and licensing activities are often pointed out as central mechanisms for making science useful.

However, this only captures a selected part of the effects of academic R&D. The science policy literature shows us that academic research and development (R&D) comes into use not only through patenting, licensing and spin-offs, but in diverse ways (e.g. Nelson and Winter, 1977; Salter and Martin, 2001). Moreover, understanding the effects of academic R&D requires consideration of influences from the surrounding environment in which academic R&D activities are undertaken (Arnold, 2004; Martin and Tang, 2007). Thus, capturing and explaining these effects requires a holistic perspective.

The technological innovation systems (TIS) approach provides such a holistic perspective to the industrialization of a technological field. Using this framework, the effects of academic R&D may be captured through their contribution to the dynamics of a TIS (Jacobsson, 2002). This approach has proven useful in studies analyzing the role of academia in the development of a set of emerging technologies (e.g. Hellsmark and Jacobsson, 2009; Mohamad, 2008; Suurs, 2009).

Nanotechnology is a highly science based emerging technology where academics have been important actors (Fogelberg, 2002). Although nanotechnology has a great potential for creating growth and other societal benefits, there are many challenges to realizing these (European Commission, 2009; OECD, 2009; Swedish Government, 2008). Given the central role of academics in the development of nanotechnology, analyzing the impact of academia becomes fundamental when understanding these challenges. Thus, nanotechnology is a suitable technology to focus on in exploring the viability of a conceptualization for capturing and explaining the effects of academic R&D.

This thesis has a methodological as well as an empirical purpose. First, it explores how the effects of academic R&D can be captured and explained. Second, it examines how these effects come about in the case of nanotechnology in Sweden. This includes analysing what hinders academic R&D from having an impact and how policy can reduce various obstacles.

The research questions are explored in two papers. The first one suggests a systemic conceptualization for capturing and explaining the effects of academic R&D. A literature analysis is conducted underpinning the conceptual framework. The second paper focuses on the empirical

[2] This debate is concerned with public investments in academic research and the value of these. Hence, the thesis focuses on academic research and not on academia's role as an educator. Often, these two are, however, closely intertwined.

purpose of the thesis and is conducted as a case study utilizing the conceptualization as an analytical framework.

This thesis starts by summarizing the two papers and their interconnections in section 2. In section 3, the conclusions from the analyses in the thesis are presented. Based on these, some methodological (section 4) and policy (section 5) reflections are made. The thesis ends by suggesting areas for further research in section 6.

2. Overview of the two papers and their connections

2.1. Towards developing a systemic framework for capturing and explaining the effects of academic R&D

Paper one deals with the analytical problems underlying the belief of poor utilization of the results of academic R&D and the focus on academic entrepreneurship, patenting and licensing as central mechanisms for making science useful. The purpose is to go some way towards developing a conceptual framework that captures and explains the effects of academic R&D.

Technological innovation systems

The technological innovation system (TIS) approach is taken as a point of departure. In particular, the thesis builds on the 'functions of technological innovation systems' framework (e.g. Bergek et al., 2008a; Bergek et al., 2008b). In the following, the conceptualization of the TIS (i.e. the structure of the system and how the system performs) is explained, illustrated as black details in figure 1.

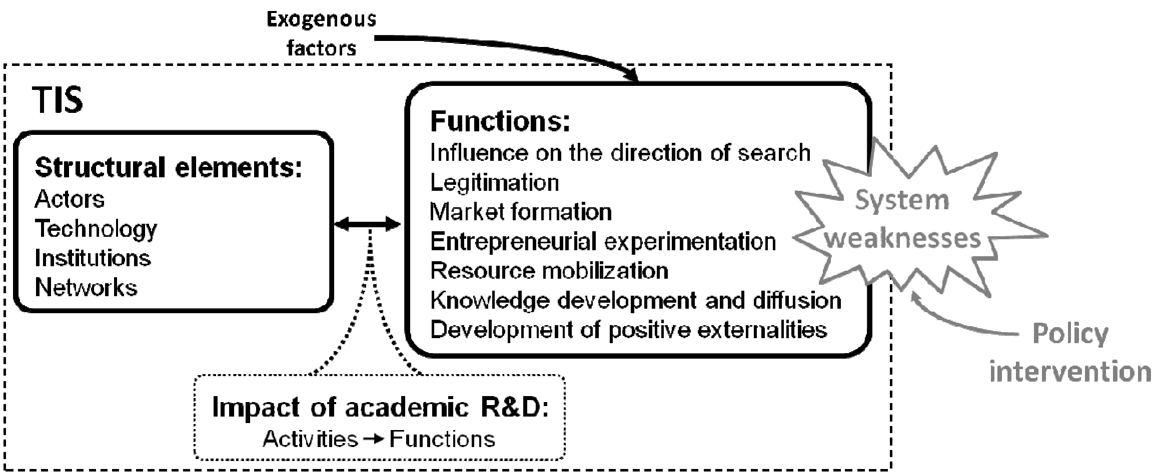

Figure 1 The 'functions of technological innovation systems' framework extended with the impact of academic R&D, developed from Hillman and Sandén (2008) and Bergek et al. (2008b).

The structural elements of the TIS are the *actors* (e.g. firms, universities), the *technology* (e.g. artifacts, coded and embodied knowledge), *institutions* (legal and regulatory aspects, culture and beliefs) and *networks* (e.g. political or learning networks) (Bergek et al., 2008b).

The 'functions of technological innovation systems' framework presents seven key processes in a TIS, called 'functions' (Bergek et al., 2008a). *Influence on the direction of search* is the process by which new actors are induced to populate the TIS and choose particular lines of development within it.

Visions, perceived growth potential, policy incentives, requirements from leading customers, crises in current business, etc. may be the inducement mechanism. *Legitimation* is influenced by socio-political actions of organisations and individuals that create acceptance and a perception of desirability for the technology or industry. Through *market formation*, markets develop from "nursing" or niche markets to bridging and mass markets. *Entrepreneurial experimentation* is the process that develops new opportunities and creates applied knowledge through testing of new technologies, applications and markets. Experiments materialise the opportunities that the technology presents and create a pool of options that helps the TIS meet uncertainties. *Resource mobilisation* refers to the mobilisation of financial and human capital and complementary assets. *Knowledge development and diffusion* relates to the creation, diffusion and combination of knowledge in the system. *Development of positive externalities* is the process by which "free utilities" emerge in the system, i.e. when investments by one actor benefit others without further costs. For example, the resolution of uncertainties, emergence of pooled labour markets and strengthened legitimation may pave the way for positive externalities. Externalities magnify the strength of the other functions. Collective actions, networks and the socio-cultural capital are essential in creating externalities.

The structure affects the performance of these functions and vice versa, indicated by the two way arrow in figure 1. Exogenous factors, such as a financial or an environmental crisis, also affect the functions. For instance, a new political network (structure) is created that powers the process of 'legitimation' (function). Together with an ongoing environmental crisis (exogenous factor), the strengthened legitimation may help align institutions (structure) to the new technology. This may result in a powerful process of 'influencing the direction of search' (function) which may induce firms to enter into the system (structure) and so the system unfolds. The interplay between structural elements, the functions and exogenous factors conceptualizes the system dynamics, i.e. how the system performs.[3]

The objective of a TIS is to develop, diffuse and utilize new products and processes related to a particular technology (Bergek et al., 2008a).[4] System strengths and weaknesses related to achieving this objective will show in the system dynamics. These strengths and weaknesses guide the analyst in identifying exogenous or endogenous mechanisms inducing or blocking the development of the system. These could be underdeveloped networks and institutions (blocking), a favourable public debate or a strong leading customer (inducing). System weaknesses and the related blocking mechanisms can guide policy actors in intervening to support the development, diffusion and utilization of new products and processes in the TIS (Bergek et al., 2008a). Policy intervention could, for instance, promote the development of networks or alignment of institutions. These analytical steps of identifying blocking mechanisms and policy interventions are illustrated as gray details in figure 1.

[3] This could be seen as a tentative model of a TIS. However, this framework was developed as an analytical construct to better understand system performance (Bergek et al., 2008a). Hence, it does not attempt to represent a thorough model of an existing system.

[4] This does not imply that there is an optimum for the system. There is no optimal system performance that the system, or individual elements in the system, strives to achieve.

The framework presented in this thesis deepens the understanding of how one of the actors in the TIS, academia, affects the functions and, hence, the development of the TIS.[5] This focus on the role of the activities of one particular actor is illustrated as dotted details in figure 1.[6]

The impact of academic R&D on the functions

Academia performs activities embedded within or sprung from R&D.[7] Seven activities were identified. Academics *conduct research* in different types of set-ups, for example through joint R&D projects or contract research. They carry out *scientific publishing* of papers, books and reports, including related tasks such as reviewing. *Educating* is often directly associated with research and includes undergraduate, Masters and PhD student training, as well as collaborative and contract training. Academics *provide direct guidance* to policy and industry actors through formal and informal consultations and as advisory board members. The guidance may regard research agendas or specific technical matters. Guidance can also be provided by participations in public debate through non-scientific publications, media appearances and at public conferences. *Commercialisation* refers to the processes of creating new firms, patents, licences, products, processes and services. Additionally, academics *provide research infrastructure* such as instruments, laboratories, clean rooms, libraries, engineering designs and methods, as well as methods of doing research. Finally, academia undertakes *networking* activities such as organising and participating in conferences and seminars.

To capture what is known about the impact[8] of these activities on the TIS dynamics, an extensive literature analysis was conducted. The data was structured in a matrix with the seven activities on one axis and the seven functions on the other. The matrix is presented in figure 2.

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[5] The focus on the impact of academia does not imply linearity in the process of innovation. The TIS approach involves links and feed-backs between the structural elements and the functions. The impact of academic R&D on the functions is only one such link.

[6] The activities of academia may also affect the structure of the TIS. For instance, they create networks and spin-off companies (actors). However, the framework presented in this thesis focuses on how the activities impact on the functions.

[7]These activities are identified out of classifications of what academic researchers do as presented by Cohen et al. (2002), D'Este and Patel (2007), Faulkner and Senker (1995), Jacobsson (2002) Meyer-Krahmer and Schmoch (1998), Molas-Gallart et al. (2002), Pavitt (1998) and Salter et al. (2000).

[8] Since both functions and activities are interdependent, indirect impacts are also possible, but these are not included in the matrix. An example of these indirect effects is given in the end of this section.

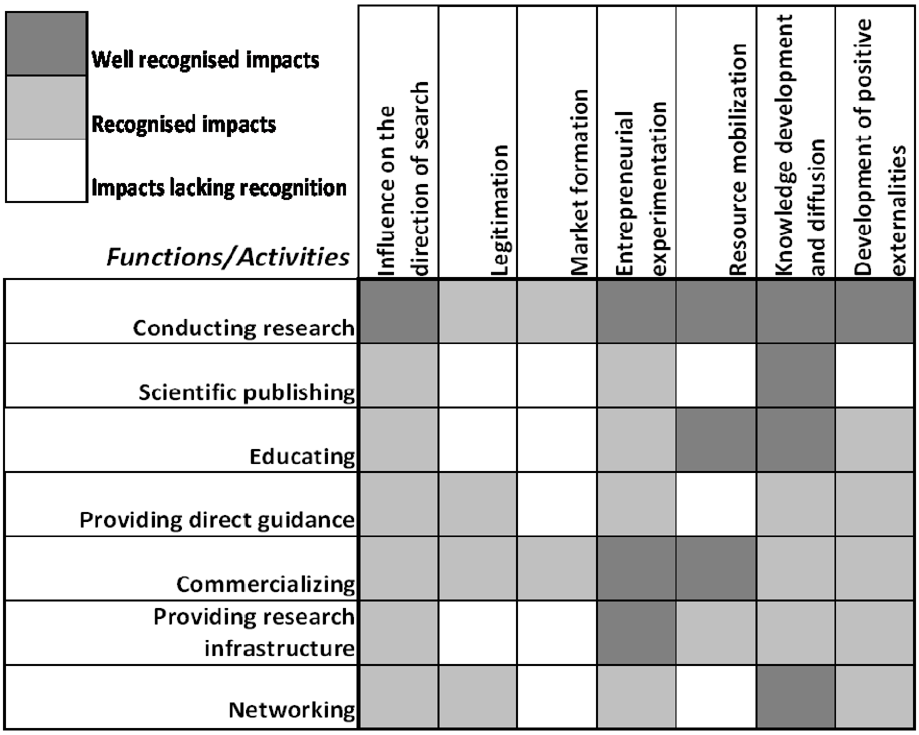

Figure 2. Mapping the direct impact of academic R&D on the functional dynamics of a TIS

The matrix was 'filled' according to references in the received literature. Each point of impact was given a level of recognition according to the number of references that identified it; lacking recognition (no references), recognized (1-10 references) and well recognized (more than 10 references).

37 out of 49 points are recognized, revealing a very large number of ways in which academic R&D has been argued to be useful.[9] *Knowledge development and diffusion*, *resource mobilization* and *entrepreneurial experimentation* have strongly recognized impacts. The subtle, but yet important functions of *influence on the direction of search, legitimation* and *development of positive externalities* also have a large number of recognized points.

As previously stated, not only academia, but all other TIS elements and exogenous factors contribute to the dynamics of the TIS. These other factors may induce or block the development of the system, conditioning the impact of academic R&D. For instance, if the system has achieved a momentum it may have a well developed capacity to demand and make use of academic R&D. If there are factors blocking the system growth, the impact of academic R&D, even if brilliantly performed, would be undermined.

Thus, the impact of academic R&D is conditioned by factors that may be beyond the reach of academics. These conditions may change over time. There are also extensive time lags between the initial activities and the full effect of academic R&D, often involving several decades (Jacobsson et al.,

[9] These figures should not be seen as exact ones, given possible problems of overlaps between functions and methodological limitations.

2010). Hence, varying time perspectives might lead to different observations on the type and extent of impacts.

Although the matrix focuses on the direct effect of academic activities, indirect effects may as well be observed. For instance, an educational activity may initially be judged to have a limited, though notable, impact on *resource mobilisation* in the form of human capital. With a time lag, these students may turn into policy makers. In this role they may have a significant *influence on the direction of search* of the TIS. These policy makers may also influence *resource mobilisation* if new funding is directed to the TIS. The example illustrates the diversity of effects of academic R&D, including direct and indirect impacts. Together with an often substantial time lag, this makes it hard to capture and explain the impact of academic R&D.

2.2. The influence of academic R&D on the commercialization of nanotechnology in Sweden

The second paper analyses how academic R&D influenced the commercialisation of nanotechnology in Sweden by capturing and explaining its impact on the growth of the Swedish nanotechnological innovation system (nano-TIS). The paper also identifies obstacles that reduce this impact and policy interventions that can enhance it.

This case study utilises the framework from the previous paper. It takes the technological innovation system approach as a point of departure, and captures and explains the effects of academic R&D through the impact of academic activities on functional dynamics. Data is collected from semi-structured interviews, workshops, seminars and from secondary sources, such as reports, books, scientific articles and media.

The impact of academic R&D on the functions of the Swedish nano-TIS

A wide range of academic R&D activities are conducted in the Swedish nano-TIS. The observations from the data are structured in the matrix developed in the first paper.[10] The data reveals 32 points of impact from activities on functions, as seen in figure 3.[11]

[10] Data was collected from seminars, workshops, conferences, secondary sources and from 35 semi-structured interviews with key members of the TIS. 18 of these were with leading researchers. Roughly 700 academic researchers are active in nanotechnology (Dahlöf and Wihed, 2009). Hence, this is only a small selection of researchers. However, twelve out of these could be regarded as prominent research leaders and all five universities with the largest nanotechnology activity were represented.

[11] One example of a point of impact was sufficient to classify it as "identified" in the matrix.

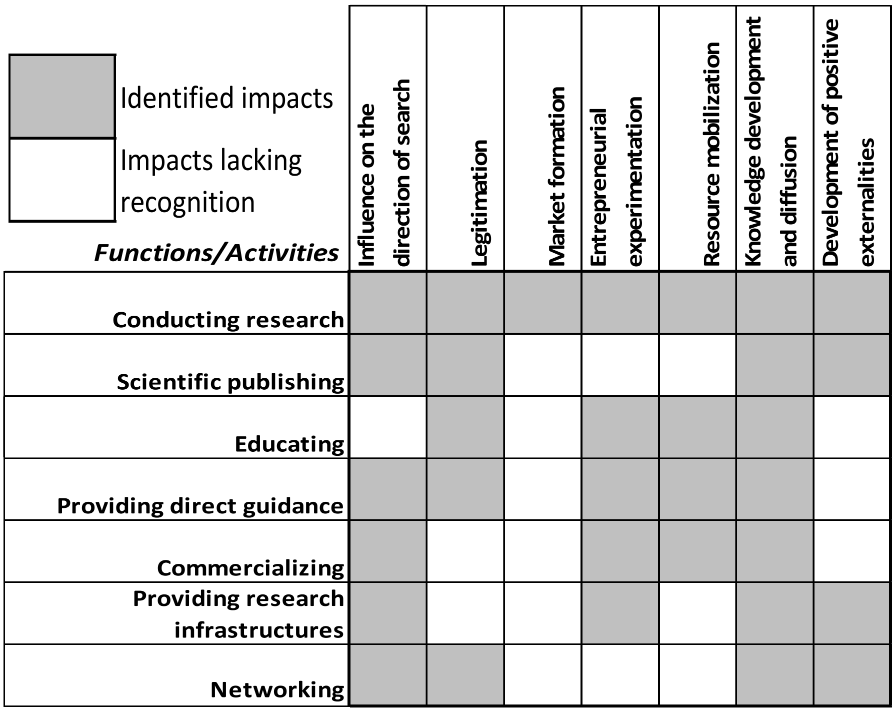

Figure 3. Impact of academic R&D on the functions of the Swedish nano-TIS.

The function *knowledge development and diffusion* reveals impacts from all the seven activities. *Influence on the direction of search*, *legitimation* and *entrepreneurial experimentation* are also impacted by many activities. *Resource mobilisation* and *development of positive externalities* reveal impact from four activities, while only one activity impacts on *market formation*.

The strengths of the functions are not only determined by academics activities but also by the other structural elements in the TIS and by exogenous factors. Some of these constitute blocking mechanisms. As functions are interdependent, the effects of a given blocking mechanism may be magnified. In the following, some examples of the processes observed in the system are presented.

Influence on the direction of search and *legitimation* are central functions, although subtle and difficult to measure. Academic researchers have addressed these functions with a broad range of activities. Still, they remain weak, blocked by uncertainties regarding environmental and health effects, institutions and markets. Inertia among research funders and lack of coordination amongst policy actors constitute further blocking mechanisms. *Entrepreneurial experimentation* is a fairly strong function with a substantial impact from academia as is *resource mobilisation* with respect to human capital. Academia has many activities geared at *knowledge development and diffusion* and the function is quite strong, but there are still significant blocking mechanisms.[12]

Influence on the direction of search and *legitimation* affect many other functions through interdependencies and are particularly important in the early development of a TIS (Bergek et al., 2008a). In this case, they weaken *Entrepreneurial experimentation* since established firms, with some

[12] For reasons of space, only the impacts on five of the seven functions are presented in this section, excluding market formation and development of positive externalities.

exceptions, are hesitant to experiment. The mechanisms that obstruct *entrepreneurial experimentation*, in turn, constrain the effects of academic activities geared towards *resource mobilisation* and *knowledge development and diffusion*. A possible surplus of human capital and knowledge generated by academia reflect a lack of demand amongst industry. More extensive experimentation from established industry would arguably increase the impact from academic R&D.

Improving the impact of academic R&D

By identifying mechanisms that block the development of the TIS, policy makers are provided with guidance on opportunities for policy intervention.

Policy may support knowledge development on potential environmental and health risks to facilitate resolving *uncertainties regarding environmental and health effects*. Policy may also support the development and implementation of regulatory frameworks to resolve *institutional uncertainties*. By facilitating the formation of nursing markets, *market uncertainty* can be addressed. Further, policy may strive to increase policy coordination to address the *inertia and lack of coordination amongst policy actors*. Policy may also mobilize *resources for verification and scaling up production*, as well as support the *development of networks*. [13]

Individual patterns of impact[14]

The analysis resulted in two additional observations relevant to the larger context of the thesis; variations in impacts of researchers and research groups on the development of the TIS and complementarities between these impacts. The following examples illustrate these variations in impacts and the complementary role of researchers and research groups.

Professor Per Delsing at Chalmers University of Technology conducts fundamental research in quantum physics (Chalmers University of technology, 2009). He *influences the direction of search* of academia, pushing the research frontier forward. He also provides research infrastructures through theoretical models that facilitate the *knowledge development* of other researchers (Swedish Research Council, 2005). Professor Lars Hultman at Linköping University has fostered a close relationship with industry continuously providing guidance that *influences the direction of search* and *entrepreneurial experimentation* of these companies (Hultman, 2009). Professor Eva Olsson is an experimental physicist at Chalmers University of Technology providing research infrastructures

[13] The analysis also has implications for business strategy. According to work on the infrastructure of entrepreneurship (Van de Ven, 1993), it is in the interest of companies that the system develops. Realizing the potential impacts of academic activities is an important dimension of system development. Advocating for policy to address relevant issues is, therefore, an essential task for business actors. Companies may take an active role in developing regulatory frameworks through increased in-house research on risks with nanotechnology products, in collaboration with academia, and openly sharing the results. Companies can also be proactive in the development of nanotechnology by integrating environmental and health risk assessment with the research and development process. Companies are essential in the development of standards; an important element in solving market and institutional uncertainties. Companies can also support probing processes by setting aside resources for experimentation. In this regard, collaborations with academia and other actors to develop potential nanotechnology applications can also mobilise resources. Further, collaborations with other industrial actors can mobilise resources for scaling up production.

[14] These observations were not included in the second paper due to reasons of space.

through instrumentation for further *knowledge development* (Swedish Research Council, 2005). This also opens up new areas of research, thus *influencing the direction of search*.

Professor Lars Samuelson belongs to a research group in semiconductor physics at Lund University. The group is internationally well recognized, creating *legitimation* for the technology in Sweden (Swedish Research Council, 2005). His group has also provided research infrastructures through developing methods for nanoimprint lithography that resulted in both further *knowledge development* and *entrepreneurial experimentation* (Swedish Research Council, 2005). Professor Bengt Kasemo at Chalmers University of Technology conducts research in chemical physics. He fostered a close collaboration with established industry, *influencing the direction of search* of these companies, and spurred *entrepreneurial experimentation* (Kasemo, 2009). He is a frequent participant in public discussions, debates and policy advisory boards, thus, strengthening the *legitimation* and *influencing the direction of search* of the area.

These examples clearly show how different researchers and research groups achieve different patterns of impact on the development of the TIS. Since researchers perform different types of activities, variations in impact can be expected.

An explanation to these variations of activities might be found in limitations to conducting a wide range of activities due to constrained resources. In a smaller research group, a focus on some activities may, therefore, come at the expense of others (Edström, 2009; Olsson, 2009). The capability to work with specific activities, or a wider set of activities is influenced not only by the size of the research group but also by the characteristics of the specific scientific or technological area, as well as by attitudes and experiences.

The examples also show how researchers and research group's specific variety of activities, and thus pattern of impacts, complements the activity of other researchers. As activities are interdependent, the activity of one researcher or research group may be essential to that of others, both within and outside the university or institution. For example, the instrumentation developed by Professor Eva Olsson's group is essential to the research of others (Swedish Research Council, 2005). Another example is the research and development of a particular nanomaterial conducted by Professor Lars Hultman's group, which heavily drew on the basic research by an external group (Liljenberg, 2008). These complementary roles imply that the impact of one individual or group is intertwined with that of others – there is as a division of labour within the system.

2.3. The connections between the papers

The two papers are connected by the conceptual framework for capturing and explaining the effects of academic R&D that constitutes the central element of this thesis. The first paper introduced this framework. The second paper is a qualitative case study utilizing the framework. Thus, the second paper implicitly explores the viability of the framework on the emerging Swedish nanotechnology TIS, as can be seen in figure 4.

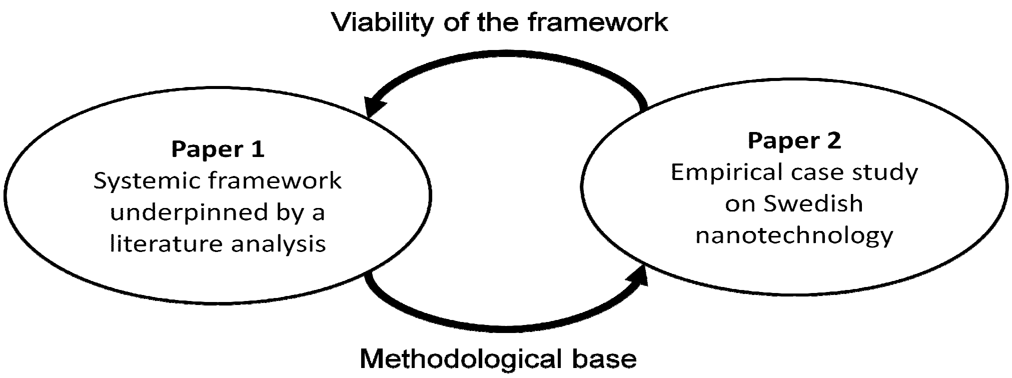

Figure 4. The relation between the two papers

When comparing the literature analysis to the empirical case study, some observations can be made. Each paper resulted in a matrix. Differences in the identified impacts of the two papers appear as discrepancies in the created matrixes, as seen in figure 5.

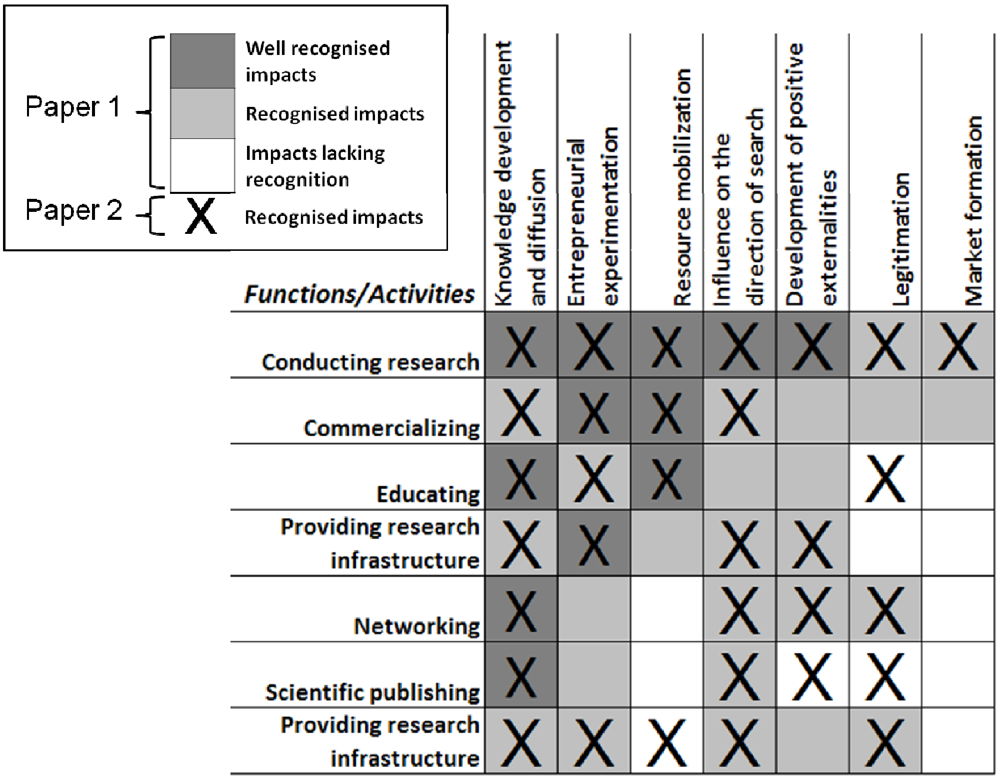

Figure 5. Comparing the matrixes from papers 1 and 2.

In the figure, the order of the functions and the activities has been rearranged to better illustrate the distribution of recognized points of impact.[15] A majority, 28 out of 49 points of impact, are recognized in both papers. 37 points are recognized in paper 1 and 32 in paper 2. The figure reveals well recognised impact in both papers on *knowledge development and diffusion*, a quite expected result, as is the well recognized impact from *conducting research*. The impacts on *entrepreneurial*

[15] The functions are ordered descending regarding the number of well recognized points of impact from paper 1. Activities are ordered on the same premises but from left to right.

experimentation and from *commercialisation* are also well recognized. *Influence of direction of search* and *legitimation* stand out with very few well recognised impacts in the literature analysis but with quite wide impact in the case.

Four points of impact recognized in the case are not recognized at all in the extensive literature analysis. Two of these are found in the *Legitimation* function. The empirical case showed how academia created legitimacy by setting up educational programs and through success in publishing. Since less interest has been paid to this function in the literature, it is possible that the received literature has failed to identify all potential impacts. This suggests that academia may play a larger role in legitimation processes than previously recognized in literature. Activities related to *providing direct guidance* geared at the function of *resource mobilisation* make up the third point of impact recognized in the case study and lacking recognition in the literature study. The case study showed that researchers directed new resources to the area through influencing the design of publicly and privately funded research programs. These guidance activities have also been given less attention, implying a possible failure of capturing this impact in existing literature. The fourth unrecognised point refers to *scientific publishing* as a signalling effect that facilitates network creation. New links between actors were established through publishing activities. This is central to the function of *development of positive externalities*.

Nine points of impact recognized in the literature analysis lack recognition in the empirical paper. Either the data for this analysis is too narrow to capture these effects, or academia has in fact been unable to achieve impacts on these points. Three of these are found in the function of *development of positive externalities*. This function may be seen as an indicator of the overall dynamics of the system (Bergek et al, 2008a). Lack of recognition in this function may suggest that the nanotechnology TIS is in an early stage of development. *Commercializing* stand out as an activity with three points lacking recognition in paper 2, but not in paper 1. For instance, the first paper identifies the role of academic spin-offs from prominent academic milieus that enhances legitimacy. This could not be confirmed in the empirical case. The remaining four points of impact lacking recognition in the second but not the first paper are spread over three functions and four activities.

The two papers share eight points of impact that lack recognition, of which five concern the function of *market formation*. This thesis may fail in capturing these effects due to limited data, or academia has in fact been unable to achieve direct impacts on these points.[16] Regarding market formation, previous studies (Hellsmark and Jacobsson, 2009; Mohamad, 2008) have shown weak academic influence on the function. This illustrates that there are limitation to the way that academia can impact the TIS development.[17]

[16] Since activities and functions are interlinked, some of the points of direct impacts that lack recognition may be indirectly impacted by academic activities. For instance, human capital educated by academia and employed by industry may perform activities that strengthen market formation.

[17] See section 5.1 for a discussion on policy implications related to these limitations.

3. Conclusions

This thesis has two research questions. Firstly, it explores how the effects of academic R&D can be captured and explained. Second, it examines how these effects come about in the case of nanotechnology in Sweden, including understanding what obstructs these effects and how policy can overcome the obstacles. The thesis also has implications for research evaluation.

As for the first research question, the first paper conceptualises the effect of academic R&D by enriching the TIS approach with a classification of activities sprung from academic R&D. This conceptualization not only captures the immediate impact on the structure of a new TIS (creating networks and strengthening the actor and technology base) but also on seven functions of a TIS. A literature analysis recognized a wide range of impacts that academic R&D may have on the seven functions. In a 7 x 7 matrix, where each activity is potentially linked to each function, 37 points of impact were recognized. This outlined a way of capturing the diversity in the channels through which academic R&D is made socially useful and the many types of effects accruing from academic R&D.

This great diversity of the types of impact of academic R&D goes much beyond conventional indicators of impact, such as the number and growth of academic spin-offs or number of patents and licences. Of particular interest were the impacts related to less tangible functions; *influence on the direction of search, legitimation* and *development of positive externalities*.

The other structural elements in the TIS and exogenous factors condition the realisation of potential impacts of academic R&D. To fully explain the impact of academic R&D, it is necessary to take this wider context in to account. The measurable impact in terms of economic growth or other structural changes is also determined by this context. This presents a great challenge when capturing and explaining the impact of academic R&D. This conceptualization deals with this challenge by identifying the impact from the contribution of activities of academics to functional strength rather than to structural change and economic growth. The conceptualization may to some extent also handle problems concerning long time lags when evaluating the impact of academic R&D. The ‘functions of technological innovation systems’ approach captures changes in functional patterns before structural changes appear. Impact on functional dynamics may, therefore, be perceived as signals of potential structural changes (Sandén et al., 2008).

The second research question deals with how the effects of academic R&D come about in the case of nanotechnology in Sweden, including understanding what obstructs these effects and how policy can overcome the obstacles. The effects are conceptualised as the impact of academic R&D activities on functions of the Swedish nano-TIS.

All seven types of academic R&D activities were identified in the TIS. Each of these impacts on at least three functions in the system, and all functions are impacted by academia through at least one activity. In total, 32 points of impact were recognized. Thus, academia’s societal benefits go much beyond a limited set of activities or functions, such as commercialization or knowledge creation.

Although a wide variety of activities were geared at many functions, the impact of academia on their development is constrained by blocking mechanisms. The effect of these may be magnified by the interdependencies of functions. For example, a wide set of activities were geared at *influencing the* *direction of search* and *legitimation*, but the impact was weakened by blocking mechanisms. In turn, these two functions influence many of the other functions.

Policy may enhance the academic impact by addressing blocking mechanisms. For example, policy may support knowledge development on potential environmental and health risks to facilitate the formation of nursing markets and support verification and scaling up of production.

This thesis also has implications for the evaluation of researchers and research groups. Firstly, researchers and research groups undertake different types of activities, thus, their pattern of impacts vary. Secondly, the impacts of individual researchers and groups are intertwined with that of academic colleagues through their complementary roles in a division of labour. Thirdly, the impact of academia is conditioned by the performance of other type of actors and elements in the TIS. It is thus be misleading to analyse the impact of researchers in isolation from other researchers or the larger context, or targeting a limited set of effects, such as commercialization or knowledge creation. Of this follows that simplistic indicators, such as number of papers published or number of spin-off firms generated fail to capture and explain intertwined and wider impacts, as well as the influence from the rest of the TIS. Supporting earlier work, e.g. by Arnold (2004) or Martin and Tang (2007), this thesis emphasizes the need for a holistic approach when capturing and explaining the impacts of academic research and development for individual research groups or for the academic sector at large.

4. Methodological reflections

Several methodological reflections emerged when applying the framework for studying the academic impact on the Swedish nano-TIS. Firstly, there are some challenges for delineating the TIS for a generic field such as nanotechnology. Secondly, some reflections on the sequence of analysis, i.e. the order of steps in conducting the study, emerged. Thirdly, some overall reflections on the viability of the conceptualization as an analytical framework are made.

4.1. Delineating the nanotechnological innovation system

The framework of this thesis builds on the innovations systems framework. The initial step in such an analysis is to delineate the system (Bergek et al., 2008a; Carlsson et al., 2002).[18] This can be based on three different levels of analysis; the *knowledge field*, the *product or artefact*, or a *set of related products* (Rickne, 2000).

The definition and delineation of the nanotechnology field is a much discussed matter.[19] Nanotechnology transcends traditional boundaries of science and technology (Wood et al., 2008). It is, thus, not a single knowledge field, but consists of a variety of sciences and technological areas.

[18] The delineation of a system is an iterative process, where the initial delineation is revised as the author's knowledge of the system develops.

[19] Even though no commonly accepted definition of nanotechnology exists, the International Organization for Standardization has presented a working definition. It encompasses "the understanding and control of matter and processes at the nanoscale, typically, but not exclusively, below 100 nanometers in one or more dimensions where the onset of size-dependant phenomena usually enables novel applications" (Palmberg et al., 2008 p. 5).

Neither is it a set of related products since it ranges over a great number of end-uses. Nanotechnology can be seen as *a set of related technologies or knowledge fields.* They are related in the sense that they make use of the set of size-dependant phenomena that typically, but not exclusively, emerge below 100 nanometres. The technologies included into the concept of nanotechnology change over time, as does the relationships between them (Palmberg et al., 2008). A detailed analysis of each technological field was not possible to produce in this thesis.[20] Consequently, the system boundaries become blurry and somehow arbitrary, based on the authors informed perceptions of the area in Sweden. Uncertainties in the analysis remain given the difficulty of delineating the system.

4.2. The sequence of analysis

After delineating the system, the next step for the analysis might be hard to identify. The first paper presents a conceptualization, but does not suggest a sequence of analysis, i.e. in what order the analysis should be undertaken.[21] The analysis includes a set of different analytical constructs that are entangled, such as structure, functions, activities, external factors and blocking mechanisms. To fully understand the characteristics of one construct requires an understanding of all the others. This creates a challenge for finding a suitable sequence of analysis.[22]

Two options for the sequence of analysis are identified. One is to start by mapping the system at large, the structure and the functional pattern.[23] The second step would be to map the academic R&D activities and how they impact on the functional pattern of the system. This emphasises the importance of understanding the system before analysing the role of academia. However, this may result in a very extensive analysis.

Another option is to start by mapping the activities of academia, continuing with the structure and functionality of the system, and finally the impacts of the activities. This keeps the focus of the analysis on academia. Still, there is a risk of biasing the analysis by assigning academia a stronger role in the system since a focus of the analysis might affect the observations made.

In this case, the thesis author had pre-existing knowledge of the system. Thus, the first of the two options were followed. This resulted in a quite rich and extensive analysis that was hard to fit into one single paper. The description had to be cut down extensively.

There is also a challenge in handling all components of the conceptualization in an analysis. The matrix allows for 49 possible points of impact. It might be demanding to gain an understanding of

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[20] Rickne (2000) drew the same conclusions for the field of biomaterials. She did not mention the case of nanotechnology in particular, but the case of biomaterials has similar characteristics.

[21] The order of presentation of the analysis does not have to follow the analytical scheme. These two may for instance differ depending on the research question, reasons of space and the pre-existing domain knowledge of the author.

[22] This creates an additional challenge when presenting the analysis. References between the different analytical constructs (activity, function, blocking mechanisms) are needed to present observations. This may become highly repetitive and result in an extensive description.

[23] A detailed methodology for this has been presented by Bergek et al (2008a).

each of the points and include insights of the larger system performance in the same study. If time is limited, the analysis can be focused on selected impacts from a limited set of activities or functions.

The analysis may be simplified by leaving out a thorough mapping of the structure, since the key constructs are the activities and the functions. However, the authors experience from conducting innovation system analysis is that mapping the structure is a natural starting point.[24]

4.3. The viability of the framework

The second paper of this thesis explores the viability of the conceptualization presented in the first paper as an analytical framework for capturing and explaining the effects of academic R&D.

The conceptualization proved useful in capturing a diverse impact from academic R&D on the development of the TIS. It gave a broad picture of how different researchers work and create benefits. Impacts on both expected processes, such as *knowledge development* and *entrepreneurial experimentation*, and more subtle but important ones, as *influence on the direction of search* and *legitimation*, were identified. The conceptualization proved useful in understanding the indirect effects of academia through the interdependencies between functions or activities. It allowed exploring how the impacts were obstructed by blocking mechanisms, such as exogenous factors and the actions by other actors.

Thus, the conceptualization is viable for identifying key aspects of the impact of academia on the emerging properties of the system. It clearly brought forward diverse policy implications for improving the effects of academic R&D, and the performance of the system at large.[25]

However, utilizing the conceptualization presents a set of challenges. Firstly, there is a problem with overlaps both in functions and activities. For example, providing guidance and networking are essential parts of many other activities, like education and providing research infrastructures. This makes it hard to analytically distinguish different points of impact. This was not a general problem in the analysis, but it occasionally required additional information on the particular impact.

Secondly, the identification of secondary and tertiary effects, i.e. indirect effects, is not systemically undertaken in the empirical analysis. Undertaking this presents great challenges, since it implies an extensive analysis with a long time scale. The empirical analysis is focused on capturing the *direct* effects of an activity on a function. However, some indirect effects in the form of secondary and tertiary impacts emerged naturally as part of the analysis. System dynamics, a core concept in the conceptualization, naturally captures these chains of effects. A systemic analysis of indirect effects would probably reveal a more extensive impact since more types of impacts would be identified. At the same time, the further away an impact is in a chain of effects, the more exposed it becomes to being influenced by other factors, both negative and positive. This makes it hard to distinguish the contribution of the particular impact.

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[24] It should be mentioned that even though the second paper in this thesis leaves out the description of the structure, it was the starting point of the author’s knowledge of the system and, thus, the analysis.

[25] This also opened up for identifying implications for business strategy.

Thirdly, the framework is limited to capturing and explaining the impact, excluding assessing the value of the impact. The value it is dependent on the perspective of the observer. For instance, an academic legitimizing technology A will be valuable for the system A, but may be negative for the competing system B. The value of the impact may also be dependent on how the system unfolds. A strong academic impact could possibly be very valuable for the development of the TIS at one time, but be of less value in another.

Fourth, another aspect of assessing the value of the impact regards additionality, i.e. if the absence of the activity leaves out the impact (Molas-Gallart, 2002). For example, a researcher acts as a government commissioned policy maker, legitimizing a technical field. In the absence of the academic action, would the impact be absent too, or would the system have adapted and substituted the action, resulting in the same impact?

Fifth, it is difficult to quantify the value of an impact. It is hard to identify and collect data for quantitative indicators of the point of impact, since many are subtle and qualitative in their nature. Another aspect of quantifying the impact is finding a point of reference. Without a reference, it is hard to assess the magnitude of the impact. A comparison with a TIS in another country or in another area could make up such a reference point. Some impacts, like the impact of publication on knowledge creation and diffusion, are easily quantifiable and comparable to the performance of another TIS. Others, like the impact of informal consultation on the direction of search, are very challenging to quantify. However, the framework opens up for identifying these types of impacts and discussing their importance.

Finally, the conceptualization presented in this thesis does not take into account the cost of undertaking each activity. Although some of the activities performed by academia are complementary, that is not always the case. Both the literature analysis and the case of nanotechnology in Sweden show that given limited resources in a research group, the focus on some activities may come at the expenses of others (Cohen et al., 2002; Yusuf, 2008). A consequence may be a too narrow focus on selected activities resulting in lower impacts. This, however, depends on the value of the impact and the cost of conducting the activity.

5. Policy reflections

This thesis raises a set of considerations for policy. Some general reflections emerge from the conceptual framework, while others are specifically related to nanotechnology, or areas facing similar challenges.

5.1. Policy and the conceptualization

The conceptualization coupled to the extensive literature review and the empirical case study go against the widely spread perception of a) a poor effect of academic research on economic development and b) academic entrepreneurship, patenting and licensing activities as key mechanisms for making research useful. Thus, this perception may be perceived as uninformed, suggesting a possible failure in the receiver competence of policy makers.[26]

Comparing the impact of researchers in isolation or targeting a limited set of effects, such as commercialization or knowledge creation, without accounting for possible time lags or the influence from the surrounding environment would fail to capture and explain the factual impact. A misleading perception of the impact of academic R&D may lead to misguided policies and unintended consequences. For instance, given limited resources in a research group, the focus on some activities may come at the expenses of others (Cohen et al., 2002; Yusuf, 2008). An uninformed perception may also lead to misleading expectations on academic impact, putting excessive pressure on academic researchers.

This thesis presents evidence that could lay the ground for a more informed policy perception on the impact of academic R&D. It reveals the diversity of the impact from academic R&D. It stresses the importance of having a holistic perspective when studying this impact. It also stresses the importance of more subtle, but still important impacts concerning the processes of *influence on direction of search* and *legitimation*. Further, the thesis reveals different patterns of impact among different researchers, and interdependences between these impact patterns.

Research and innovation policy needs to take these findings into account in order to have an informed understanding of the role of academia. The funding, evaluation and support system for academic research should reflect the diverse roles academic research takes. For example, the support system for creating benefits from academic researchers, which currently is dominated by incubator programs and technology license offices, should be adapted to the varying roles of academic research.

The conceptualization also revealed limitations to the impact of academia, particularly regarding market formation. However, academia is only one of many actors in a TIS. Other actors may be better suited to develop this, and other functions. In promoting the development of a TIS, policy should take this into account.

5.2. Reflections based on the Swedish nanotechnology case

Although the empirical case in this thesis showed a wide impact from academic R&D it also revealed that academia can only do so much for the development of the TIS. The case identified a number of

[26] This is not only true for policy makers, but also for researchers legitimizing this perception as policy advisors, as stressed by an experienced policy maker.

opportunities for policy intervention to improve system dynamics, and the effects of academic R&D. However, exploiting these opportunities presents challenges to policy. Even though these are drawn from studying the nano-TIS in Sweden, this may have implications for areas facing similar challenges.

Nanotechnology is influenced by many policy areas, such as research, innovation and environmental policy. Swedish governance of nanotechnology has, however, been separated regarding research, innovation and environmental policy (Fogelberg, 2008; Fogelberg and Sandén, 2008). A policy actor concerned with and capable of boosting nanotechnology related innovation processes has been lacking. The analysis revealed how this created a blocking mechanism in the system. The importance of a concerned policy actor with a holistic competence, capable of boosting the development of a new technological area transcending traditional policy boundaries was clear.

In 2009, the national nanotechnology strategy presented an opportunity of meeting these challenges. A set of agencies were commissioned to develop a national strategy for meeting risks and potentials related to nanotechnology. Taking on a more holistic perspective of the technology presented, however, challenges to the participants, to the agencies and to the concerned ministries. The process required combining different policy areas. It revealed differences in the perceptions and tasks of the different actors, and the absence of a policy actor driving the process and giving it political legitimacy (Svendsen, 2010). This partly reflected the different views and tasks of the three ministries that were involved in the process through their agencies. In particular, some resistance against change amongst the agencies was observed. Despite the fact that the need for change and coordination is indicated in the strategy document, it failed to present powerful measures.

The case of nanotechnology in Sweden illustrates a mismatch between policy task, i.e. what policy needs to do, and policy regimes, i.e. the organization of policy, as well as a reluctance to change. This could also be described as a path-dependency in the development of the Swedish research funding system, creating inertia (Benner and Sandström, 2000). New interdisciplinary research areas with new challenges, such as biotechnology or nanotechnology, presents fundamental challenges to the existing public sector research system. These challenges often require the coordination of different policy bodies. The Swedish policy system consists, however, of small governing ministries that delegate detailed policymaking to the agencies through bills (Thorslund et al., 2005). The responsibility of coordinating is consequently assigned ad hoc to the agencies, without continuous mechanisms for coordination in place. It often comes down to the interest and capability of individuals to undertake these processes. This makes it hard for a new technological area to gain foothold.

Literature on innovation and research policy recognizes this need for the policy regime to reflect the policy tasks. Carlsson and Jacobsson (1997) state that policy tasks should reflect the current market, network and institutional failures (system failures). However, policy organizations serve under a certain kind of regime built on older policy tasks that in turn were answers to older system failures. This dynamics can be seen in the light of the description of technological regimes and regime shifts by Kemp et al. (1998). In order to implement the policy task that reflects today's system failure the current policy regime needs to change.

Coming back to the national nanotechnology strategy, it was delivered to the Ministry of Industry in early 2010. The lack of a concerned and capable policy actor acting as a receiver of the strategy has resulted in a lukewarm reception and uncertainty about the future implementation of the strategy.

This illustrates the value of a concerned and competent policy actor with a holistic competence of the area. To drive the processes of policy change a 'champion' on policy level is needed. Academic researchers have long been driving the area, acting as 'champions' for the technology. One might wonder what the incentives are for academia to create benefits, when policy responds weakly to the activities of academia. At the same time, other technological areas face other challenges that might present trade off to the development of e.g. nanotechnology. This is yet another challenge for policy to tackle in supporting the development of technologies for industrial renewal and growth.

6. Suggestion for further research

The conclusions and discussions presented in this is thesis open up for further research. Three main research paths are identified.

6.1. Further developing the analytical framework

The conceptualization of the impact from academic R&D presented in this thesis could be further developed as a systemic analytical framework for research evaluation and policy analysis. A number of issues have to be explored in order to do so. Firstly, the literature analysis left a number of points of impact without recognition. Additional work is needed to either reveal these impacts, or find reasons for their absence. This could take the form of extended literature analysis or in-depth case studies. For instance, the case study in this thesis added four point of impact that the literature analysis failed to recognize.

Secondly, the current conceptualization lacks corresponding indicators and linkages to quantitative data. Each point of impact could plausibly be assigned one or several indicators, though many points are subtle and qualitative in their nature. Such indicators need to be developed and tested. The case in this thesis mainly built on qualitative data from interviews and secondary sources. However, the conceptualization opens up for a possibility to explore and complement with more quantitative approaches, such as the use of questionnaires. Conducting a survey on a larger number of academic researchers, companies and policy actors using the matrix as a starting point would be of particular interest. In addition, the use of existing data sets, such as bibliometric data, patent data and databases on social media, would be valuable to explore.

Third, assessing the relative magnitude and type of the impact from academia on the TIS, i.e. if it is large or small, narrow or extensive, requires points of reference. Such are currently lacking. Comparative studies between different TISs or regions could be conducted to create points of reference. Reference points could also be the impact of other actors, e.g. companies or policy makers. TIS in different life cycle phases could present further possibilities of comparing impacts. As different functions vary in importance in different phases (Bergek el al., 2008a), the role of academia differ depending on the phase of the TIS.

Fourth, the viability of the framework also needs to be further tested on other delineations of a TIS, such as a sector, a product or a more specific knowledge field. Different delineations have different logics depending on a number of factors, such as knowledge intensity, capital intensity, phase in the industry life cycle, type of customers etc. It is likely that new methodological challenges will emerge from further testing the conceptualization as an analytical framework.

Fifth, the conceptualization can also be developed by exploring its viability for studying the impact of a particular researcher, or group of researchers. Though the case of nanotechnology in this thesis focused on the system at large, it revealed some examples of individual researchers' patterns of impact. Thus, although the conceptualization presented in this thesis does not explicitly focus on the individual researcher, or researcher group as the element of analysis, it opens up for doing so.[27] Also, the different researchers' patterns of impacts revealed with the conceptualization opens up for a typology of researchers' role in the system.

6.2. Exploring mismatches in policy tasks and policy regimes

The case on nanotechnology raised policy issues regarding mismatches between policy tasks based on system failures and policy regimes. In particular, this includes the need for transformation of policy regimes to conduct policy tasks. Policy organizations serve under regimes built on older policy tasks that in turn were answers to older system failures. Undertaking a policy task that reflects today's system failure most often requires a change in the current policy regime. Literature on innovation and research policy, such as Carlsson and Jacobsson (1997) and Kemp, Schot and Hoogma (1998), recognizes this. Further, Benner and Sandström (2000) showed how inertia in the public research funding system created obstacles for the development of biotechnology. Fogelberg (2002 and 2008) also stressed the mismatch between the current innovation policy regime and the challenges facing the development of nanotechnology.

It would be of interest to systematically explore how the perceptions of system failures have changed over time and how that has reflected the policy regime in Sweden. A number of research questions can be addressed. Are the same system failures targeted today as in earlier period of time? How have earlier system failures affected the current policy regime? Is there in fact a mismatch between the current policy regime and the policy tasks that address current system failures?

Finally, a more implication oriented research question regards undertaking a regime shift in policy. Are there 'successful' examples of such shifts? How can a policy regime shift be undertaken?

6.3. Extending the understanding of impact from growth to direction of a TIS

The current conceptualization recognises the impact of academic R&D as contribution to the growth of a TIS. As such a system develops, different possible trajectories, or pathways, appear in the form of application areas (Hillman and Sandén, 2008). These may vary in terms of their potential for creating benefits for society (Rafols, 2010). For instance, different pathways may have different environmental values to society. It could be argued that, given a specific technology such as

[27] Hellsmark and Jacobsson (2009) successfully studied the influence of one individual from academia on the case of gasified biomass in Austria using a similar framework.

nanotechnology, focusing on, for example renewable energy most likely brings more long term societal value than focusing on cosmetics.

Thus, the direction that a system takes influences its societal value. The framework ‘functions of technological innovation systems’ captures the direction of the system through the functions ‘influence on the direction of search’ and ‘legitimation’. This is linked to the extensive and growing discourse on governance of technology and innovation. A first step on developing a framework for analysing the governance of innovation systems has been made by Hillman et al. (2009).

Examples of how actions from academia impacted the ‘influence on the direction of search’ and ‘legitimation’ can be found in this thesis and in previous work (e.g. Hellsmark and Jacobsson, 2009; Mohamad, 2008; Suurs, 2009). This opens up for extending the understanding of the impact of academic R&D; from recognising the impact as contribution to system growth to also include the influence on the direction of the system.

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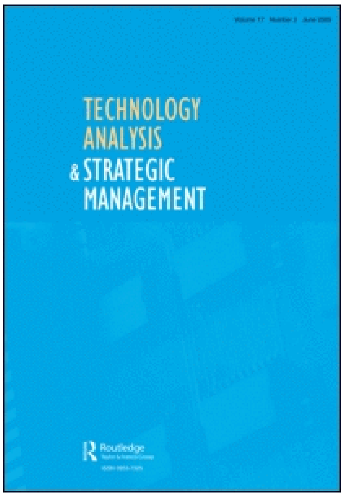

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Towards a systemic framework for capturing and explaining the effects of academic R&D

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Towards a systemic framework for capturing and explaining the effects of academic R&D

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In the EU, it is believed that the potential benefits of academic R&D are not fully reaped. Much attention is, therefore, given to enhancing commercialisation in the form of academic spin-offs, patents and licences. There are, however, a number of problems with this way of analysing the effects of academic R&D. Its contribution must instead be captured by a systems approach and we go some way towards developing such an analytical framework. This enables us to capture, explain and assess the effects of academic R&D on the dynamics of an innovation system. We apply this framework to the received literature which informs us of a great variety of impacts on such systems. Conventional indicators cover, therefore, just a small part of the full impact of academic R&D.

Keywords: industry–academic relations; technological change and dynamics; science and technology and innovation policy studies; evaluation study; technology and innovation studies

1. Introduction

This study contributes to the European debate on the role of academic R&D in industrial development (e.g. Dosi, Llerena, and Labini 2006; European Commission 1995, 2007; Geuna 2001; Granberg and Jacobsson 2006). A strong belief is that Europe has failed to reap the full benefits of its investments in academic R&D. As Dosi, Llerena, and Labini (2006, 1450) explain, the 'European paradox … refers to the conjecture that EU countries play a leading global role in terms of top level scientific output, but lag behind in the ability to convert this strength into wealth generating innovations'.[1]

Particular attention has been given to academic entrepreneurship as a central, but underutilised, mechanism for making science useful. For instance, reporting on an Organisation for Economic Co-operation and Development (OECD) survey about the formation of high-technology spin-offs from public sector research institutions, Callan (2001, 14), argued that 'The number of spin-offs generated in an economy is understood as an indicator of the public sector's ability to develop commercially relevant knowledge, of its entrepreneurial capacity, and of the depth of knowledge transfer between the public and private sectors'. A great deal of concern has been raised over the alleged poor propensity to spin off firms from academia (e.g. Goldfarb and Henrekson 2003). Attention is also given to patenting and licensing by academic researchers. For instance, the

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European Commission (2007, 3) starts its discussion about the need for action to improve the transfer of knowledge between research institutions and industry by arguing that: 'One important problem is how to make better use of publicly funded R&D. Compared to North America, the average university in Europe generates far fewer inventions and patents'.

There are a number of problems with this way of capturing the effects of academic R&D. First, there are many channels through which academic research affects society and, second, there are many types of impacts. Analysing the effects of academic R&D should neither be limited to studying the impact of spin-offs in terms of, say, employment, nor to the role of publications in providing a public good in the form of new information, as focused on in neoclassical economics (Martin and Tang 2007; Nelson and Winter 1977). Capturing the impact of academic research is instead a task that requires the mapping of a range of channels, often providing subtle and heterogeneous benefits (Salter and Martin 2001).[2]

Third, explaining the size and nature of these impacts requires an understanding of not only the actions of academics but also the larger context in which academic R&D is pursued. This context is increasingly conceptualised in innovation system terms. Consequently, the effects of academic R&D may be analysed in terms of its contribution to the dynamics of innovation systems (Jacobsson 2002). Such an approach would supplement the conventional evaluation methods involving peer reviews and econometrics (Arnold 2004; Martin and Tang 2007). Indeed, as Arnold (2004, 3) points out, '… a systems world needs system evaluations'.

Fourth, in much of the literature, there is a failure to appreciate the time lag between the point when R&D is initiated and its full impact on society (e.g. Henrekson and Rosenberg 2001).

The purpose of this paper is twofold: (1) to go some way towards handling these four problems by developing a conceptual framework that enables us to capture, explain and thereby assess the effects of academic R&D; (2) to challenge the strong belief in academic entrepreneurship, patenting and licensing as central mechanisms for making science useful by applying parts of this framework to the received literature.

The system approach we take is that of technological innovation systems with its recent extension in terms of functional dynamics (e.g. Bergek et al. 2008). Such systems are found at a meso level and Arnold (2004, 13) argues that in terms of policy evaluations 'This is the most genuinely novel of the three levels, evaluating and analysing at a meso level, to explore the systems role of institutions, of actors, clusters and so on'.

The paper is structured as follows. Section 2 explains the structure and dynamics of technological innovation systems (TIS). Section 3 extends the framework by specifying a range of activities that academics pursue in connection with R&D. On the basis of an extensive literature review, we subsequently demonstrate the large number of ways in which this R&D has been argued to affect the dynamics of a TIS. Section 4 completes the framework to include endogenous and exogenous inducement and blocking mechanisms that may help us explain these impacts. In this section, we also discuss the time scale involved in making science useful. The final section provides a concluding discussion.[3]

2. The structure and dynamics of a technological innovation system

In this section, we conceptualise the structure and dynamics of a TIS, beginning with its structural elements.[4] We then identify seven sub-processes, or functions, in the larger innovation and diffusion process. In the final sub-section, we explain how these contribute to the formation of new structures.

2.1. *The structural elements of a TIS*

A TIS is composed of four elements: technology, actors (firms and other organisations), networks and institutions. Technology is made up of artefacts (e.g. tools and machinery), coded knowledge (patents, drawings, etc.) and knowledge embodied in, for example, engineers and scientists. The firms are found within the whole value chain. Other organisations include universities, institutes, government agencies, professional organisations, bridging organisations and other interest organisations.

The networks can be of various types. We focus on learning[5] and political networks.[6] Learning networks include user–supplier networks, networks between related firms (Porter 1998) and university–industry networks. These constitute modes for the transfer of knowledge. The network also influences the perception of what is possible and desirable, i.e. images or expectations of the future, which guides specific investment or policy decisions (Carlsson and Jacobsson 1993; Geels and Raven 2006).

Political networks refer to those whose objective is to influence the political agenda, as focussed on in political science literature (Rao 2004; Sabatier 1998; Smith 2000). This literature argues that policy making takes place in a context where advocacy coalitions, consisting of a range of actors sharing a set of beliefs, compete in influencing policy in line with those beliefs. For a new technology to gain ground, technology specific coalitions need to be formed and they must engage in the wider political debate.

As actors enter the TIS, these networks may be formed, enlarging the resource base of the individual organisation (in terms of information, knowledge, technology, etc.) and giving the collective a voice in the political arena.

The fourth element is institutions. These refer to legal and regulatory aspects as well as norms and culture (North 1990). Institutions also includes beliefs (cognition) that structure search processes and influence firms' and other actors' decisions (Dosi 1982; Geels and Raven 2006; Tripsas and Gavetti 2004).

2.2. *Functions of a TIS*

The development of these structural elements is a prerequisite for the performance of the TIS. It is therefore necessary to identify the process of formation of the structural elements of the innovation system. To do so, we use a scheme of analysis labelled 'functions of a TIS', which draws on a range of disciplines, including evolutionary and industrial economics, management science, entrepreneurship, population ecology and political science.[7] Bergek et al. (2008) identify seven key sub-processes in the industrialisation of a new technology: (1) Influence on the direction of search, (2) Legitimation, (3) Market formation, (4) Entrepreneurial experimentation, (5) Resource mobilisation, (6) Knowledge development and diffusion and (7) Development of positive externalities (see Table 1).

There are overlaps between these closely linked processes which may have implications for the analysis in Section 3.2. For instance, 'legitimation' is one of many determinants of 'influence on the direction of search'. Given the emphasis put on legitimation in several disciplines, we chose, however, to award it the status of function – a key process.[8] As our understanding increases, we may add or delete functions. The list of functions, as presented in Table 1, is thus not a final one nor one that is free from our judgement.

These processes may be influenced by actors through everyday activities, such as when academics teach MSc students, impacting on 'knowledge diffusion'. The functions may, however,

Table 1. Functions of technological innovation systems

Functions		Content of the functions
Influence on the direction of search	is the process by which	actors are induced and/or pressurised to enter the technological field or to choose a particular line of development within the field. For an innovation system to be formed, new actors have to enter it. The system as a whole needs to generate variety in terms of technologies, applications and markets as well as to explore this variety. Incentives may come in the form of visions, expectations of growth potential, regulation and policy, articulation of demand from leading customers, technical bottlenecks, crises in current business, etc.
Legitimation	is the process by which	the legitimacy of the new technology and industry is strengthened through socio-political actions by organisations and individuals. Gaining legitimacy implies overcoming the liability of newness. Acceptance as a desirable technology/industry by relevant actors is necessary for the mobilization of resources, for demand to form and for actors to acquire political strength.
Market formation	is the process by which	customers articulate their demand and markets develop through various stages, i.e. 'nursing' or niche markets (e.g. in the form of demonstration projects), bridging markets and mass markets.
Entrepreneurial experimentation	is the process by which	new opportunities and knowledge of a tacit, explorative and applied nature are developed by testing new technologies, applications and markets. A variety of experiments creates a pool of options that helps the TIS meet inherent uncertainties. The experimentation includes the development and investments in artefacts such as products and physical infrastructure. Materialisation gives concrete manifestations of the opportunities that the technology presents, which may also strengthen 'legitimation', as it may raise awareness among actors of the opportunities of the technology.
Resource mobilisation	is the process by which	actors raise financial and human capital as well as complementary assets. In earlier phases of TIS development, the sourcing of specialised capabilities and capital represents a generic problem.
Knowledge development and diffusion	is the process by which	knowledge is developed, diffused and combined in the system, thereby increasing the breadth and depth of the knowledge base.
Development of positive externalities	is the process by which	the collective dimension of the innovation and diffusion process emerges, through the development of 'free utilities' (i.e. when investments by one firm benefit other firms 'free of charge'). It indicates the dynamics of the system since externalities magnify the strength of the other functions. As the system grows, positive externalities may flow as a consequence of, for instance, the resolution of uncertainties, the emergence of pooled labour markets and a strengthened process of legitimation. An aspect of this function is the build-up of networks and the socio-cultural capital that links the actors in the TIS, paving the way for reciprocal external economies (Carlsson and Jacobsson 1993). This community building may take place when a common geographic and technological frontier, or a shared background, can be identified (Saxenian 1994). Actors may then see themselves as a part of a system, with common problems and opportunities, and can grasp the importance of collective action (Bergek, Jacobsson and Sandén 2008).

Source: Elaboration on Hellsmark and Jacobsson (2009).

also be influenced by conscious system building efforts. For instance, in Table 1 we underlined the importance of socio-political action for the legitimation of a new technology. An activity in question could be a senior manager who publicly recognises the desirability of, say, 'green' nanotechnology or an academic who argues in favour of the very same technology as a consultant to the Ministry of Industry. Such 'system building activities' are recognised as being central by Hughes (1983) as well as by Porter (1998) and Van de Ven (1993) whose respective frameworks (Clusters and Social System respectively) are similar to that of TIS.[9]

Whereas various activities are closely linked to the micro-level of discrete actors, a 'system level activity' may be perceived as the sum of all micro-level activities (Markard and Truffer 2008). This 'system level activity' contributes to the strength of the functions and there are, thus, appreciable overlaps between 'activities' and 'functions'.[10] Yet, the functions are also affected by other structural elements, e.g. institutions as well as by exogenous factors (see Section 4). For instance, 'influencing the direction of search' of firms into a new TIS centred on, say, solar cells, may be affected by, for example, the articulated demand from leading edge customers (activity), policies promoting the diffusion of solar cells (institution) as well as the climate change debate (exogenous factor). We see functions, therefore, as emergent properties of the system and not merely as an aggregation of activities pursued by individual actors (Jacobsson and Bergek 2004; Markard and Truffer 2008).

Yet, the activities of actors influence these emergent properties. As pointed out by Van de Ven (1993), these actors are not only firms; the activities of interest organisations, individual policy makers and academics affect these properties as well.[11] In what follows, we will focus on the impact of a set of activities undertaken by academic researchers (Section 3.1) on the strength of the seven functions as a way of capturing how academic R&D is made socially useful.[12] Of course, a similar analysis can be performed for any actor in a TIS.

2.3. *Functional dynamics and the formation of new structures*

The impact of academics on the functions can be both direct and indirect. A direct impact would be when an academic develops a technical solution for carbon sequestration together with a utility ('knowledge development and diffusion'). Indirect effects follow from the observation that the 'functions' are not isolated processes but are interdependent (Bergek, Jacobsson, and Sandén 2008). The above-mentioned academic may, by helping a utility with an initial 'entrepreneurial experimentation', strengthen the process of 'legitimation' of carbon sequestration technology. As a consequence, the 'direction of search' of other utilities may be influenced, possibly leading to new entrants into the TIS. Hence, an initial effect may be magnified as the TIS unfolds. These secondary and tertiary effects have to be captured in an ultimate analysis of the effects of academic R&D and are, henceforth, labelled indirect effects.

Indeed, these indirect effects may contribute to the emergence of a process of cumulative causation (Myrdal 1957).[13] For instance, in the case of carbon sequestration, an emerging advocacy coalition (structure) may be strengthened by a new entrant with strong credibility in society at large (structure). Legitimation of the technology may then be enhanced (function). This may positively impact on the function 'influence on the direction of search' (function – complete feedback loop) and induce more firms to enter the TIS (structure – complete feedback loop). In turn, this may not only strengthen 'resource mobilisation' (function) but also the advocacy coalition (structure – complete feedback loop) which through an improved 'legitimation' (function – complete feedback loop) may impact on the institutional framework (structure).[14]

In sum, the internal dynamics of a TIS (exogenous factors will be added in Section 4) can be conceptualised as a set of links and feedback loops between structure and functions. As these processes unfold, they contribute to the formation of the structural elements of a new TIS. The impact of academic R&D on system formation is, therefore, not limited to the immediate effects on structural build-up in the form of new firms (actors) and patents/licences (technology). It is also mediated through *its impact on the strength of all seven functions*, where we identify both direct and indirect effects.

3. A systematic mapping of the impact of academic R&D on the functional dynamics of a TIS

Having outlined our analytical framework, we will review what the received literature has to say about how academic R&D contributes to functional dynamics. This section, thus, provides a literature based analysis of (1) what activities take place in connection with academic R&D and (2) how these may affect the dynamics of the seven functions.[15]

3.1. *Activities embedded within or sprung from academic R&D*

This sub-section identifies activities embedded within or sprung from the process of conducting academic R&D. In the literature, there are several ways of classifying what academic researchers do (Cohen, Nelson and Walsh 2002; D'Este and Patel 2007; Faulkner and Senker 1995; Jacobsson 2002; Meyer-Krahmer and Schmoch 1998; Molas-Gallart et al. 2002; Pavitt 1998; Salter et al. 2000). However, the focus is not so much on activities but rather on 'products' or 'outcomes' of academic R&D (e.g. papers, patents and artefacts). As the objective of developing this framework is to help us trace and explain the impact of academic R&D, it is necessary to distinguish between what academic researchers do and the outcomes of these activities.[16]

Drawing on the received literature, we identified seven groups of activities and divided these into 19 sub-activities, see Table 2. Combinations and variations of all these constitute everyday life for academic researchers.[17]

When conducting research, many combinations of funding and commissioning are possible. While participating in joint R&D projects, academic researchers cooperate with non-academic actors, both national and international. In contract research, the project may be entirely conducted by academics, but the research problem is commissioned and the project is financed chiefly by an external, often industrial actor (Molas-Gallart et al. 2002). In some cases, this external actor may also come from policy. The line between contract research and consultation may be blurred.

'Scientific publishing' of papers, books and reports is the traditional formal form of diffusing information in the academic world. The activity includes reviewing and other related tasks.

'Educating' is directly associated with research as it is not limited to teaching undergraduate students. First, researchers train Masters and PhD students. Second, researchers often run executive education programmes designed for industry or policy-making bodies. Third, these two may be combined in the case of industrial PhDs (D'Este and Patel 2007).

'Providing direct guidance' is an activity that is given less attention in the literature. Guidance may be provided to both policy and industry actors. The former may need academia's support in, say, advisory boards for developing research agendas. The latter may seek advice

Table 2. Activities embedded within or sprung from academic R&D*

Activities	Sub-activities
Conducting research	Conducting joint research (academia and non-academia)
	Conducting intra-academic research
	Conducting contract research
Scientific publishing	
Educating	Educating undergraduate students
	Educating PhD students and scientists
	Educating industrial PhD students
	Conducting contract/collaborative education
Providing direct guidance	Participating in policy/industrial advisory boards
	Conducting informal advisory work
	Consultation
	Taking part in public discussion and debate
Commercialising	Creating new firms
	Patenting and licensing
	Creating new products, processes and services
Providing research infrastructure	Providing physical facilities
	Developing instruments
	Developing research and engineering design and methods
Networking	Participating in networks
	Creating networks

*How we derived these activities is explained in Appendix 1 of a longer electronic version of the paper which the interested reader can obtain from the authors.

on specific technical matters, e.g. the environmental performance of ethanol as an alternative fuel. Such guidance may be given informally (D'Este and Patel 2007). It may also cover social and economic issues connected to technical choices, as well as providing frameworks and empirical underpinnings of policy (Salter et al. 2000). Additionally, guidance can be provided by academics taking part in public debate through non-scientific publications, media appearances and at public conferences (Molas-Gallart et al. 2002). Often, guidance does not require new research, but could not be carried out without a close link to research.

'Commercialisation' is divided into the processes of creating new firms, patents and licences, as well as those of creating products, processes and services even when patent or licence agreements are lacking.

'Providing research infrastructure' refers to creating the physical and intellectual tools that facilitate research work. Frequently, the process of conducting R&D is dependent on investments in physical facilities, such as laboratories or clean rooms, but also on libraries (Molas-Gallart et al. 2002), instruments (Pavitt 1998), engineering design and methods (Faulkner and Senker 1995), as well as on methods of doing research. The research activity itself develops the infrastructure as it formulates the need for it and the use of it. Industry or governmental actors may then utilise this infrastructure.

Networking, including their creation and maintenance, is performed by academia in order to facilitate other kinds of activities. The networks may give access both to national and international academics (Jacobsson 2002) and to professional groups of actors (Pavitt 1998). Organising and participating in conferences and seminars, both academic and non-academic, is a key activity. The informal dimension of networking is often stressed.

3.2. *Impact of academic activities on functional dynamics*

The impact of these activities on the seven 'functions of TIS' is illustrated in Figure 1 (marked with a bold arrow). We extend, thus, the conceptual framework of the dynamics of TIS with the list of activities detailed above (exogenous factors will be added in Section 4).

The usefulness of linking activities to functions was first suggested by Jacobsson (2002). A second step was taken by Mohamad (2006), who compared each of the 'TIS functions' in Bergek et al. (2005) with the 'impacts on innovation by universities' (Salter et al. 2000), for example by linking the 'creation of new firms' to 'entrepreneurial experimentation' and the 'training of skilled graduates' to 'resources mobilisation'. However, in Mohamad's analysis, one 'impact' was linked to one function only. This paper takes a further step by analysing the extent to which the listed activities may influence more than one function.

A matrix with seven activities on one axis and seven functions on the other was created as a conceptual map to systematically trace the *direct* impact of academic R&D on functional dynamics. We exclude, thus, secondary and tertiary effects (see Section 2.3) as well as the possibility that each activity-function link may be a part of a larger cause-effect chain, involving feedback from functions to structure, as demonstrated in Figure 1. The matrix was 'filled' by referring to the received literature.[18] Hence, this section is limited to giving a descriptive account of what the received literature has to say about the direct impact of the seven activities on the seven functions.

The literature was drawn from a broad range of fields, including 'impact assessment', 'innovation systems', 'university–industry relations' and 'the role of universities in economic growth'. We had three points of entry into this literature. First, we identified a set of articles which identified a range of impacts (Cohen, Nelson, and Walsh 2002; Jacobsson 2002; Mansfield 1995; Mohamad 2006; Molas-Gallart et al., 2002; Salter and Martin 2001). Second, articles were retrieved by combining key words in search engines.[19] Third, sources were recommended by fellow researchers.

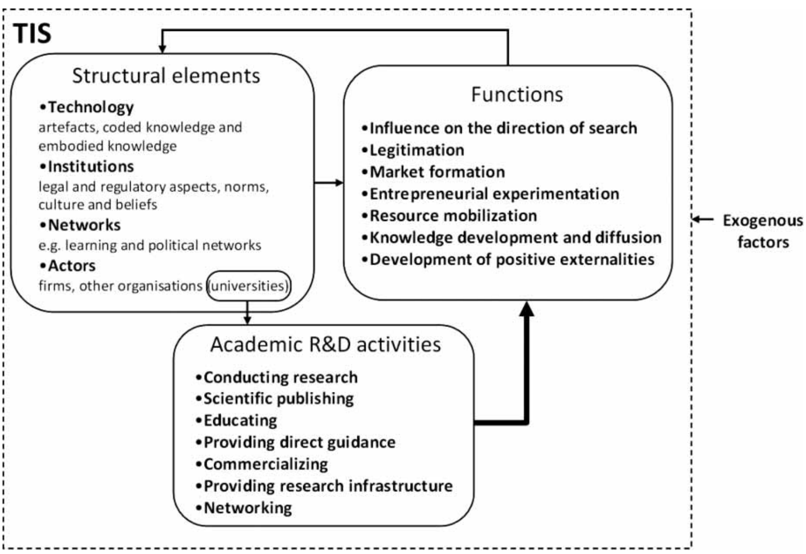

Figure 1. The impact of academic R&D on the dynamics of a TIS (the bold arrow illustrates the impact of activities on the seven 'functions of TIS'). Sources: Development of Hillman and Sandén (2008) and Bergek, Jacobsson and Sandén (2008)

From this initial literature, we traced relevant sources which were followed until a substantial part of the literature re-emerged. Seventy-four sources were ultimately selected.

The matrix in Figure 2 contains 49 possible points of direct impact.[20] The degree to which the literature recognises each point was measured by the number of sources identifying it. Three levels were used; lacking recognition (no references), recognised (1–10 references) and well recognised (more than 10 references). Given that the literature review was, by necessity, incomplete, the matrix reflects a preliminary pattern.

Figure 2 reveals that the majority, 37 out of 49, of the points have been recognised, leaving only 12 unrecognised. While ‘commercialisation’ impacts on all the functions and is, thus, a powerful activity, the main message from the matrix is that ‘the literature informs us that there are a very large number of ways in which academic R&D has been shown to be socially useful’.

An article does not allow for a discussion of each of these points of impact. Instead, we begin with discussing the three functions which have more than one ‘well recognised’ point of impact: (1) knowledge development and diffusion, (2) resource mobilisation and (3) entrepreneurial experimentation. Together, these three functions have ten ‘well recognised’ points of impact.[21] For each of these functions, we will briefly discuss the connections made in the literature between ‘activity’ and ‘function’. We will then discuss three functions with less frequently noted impact, but for which there is nevertheless clear evidence: (i) Influence the direction of search, (ii) Legitimation and (iii) Development of positive externalities.

Knowledge development and diffusion has four well recognised points of impact. First, ‘conducting research’ impacts knowledge development by providing universal theories and empirical generalisations (Gibbons and Johnston 1974; Salter et al. 2000). This lays the ground for later knowledge development (e.g. Faulkner and Senker 1994; Pavitt 2000). ‘Joint research projects’

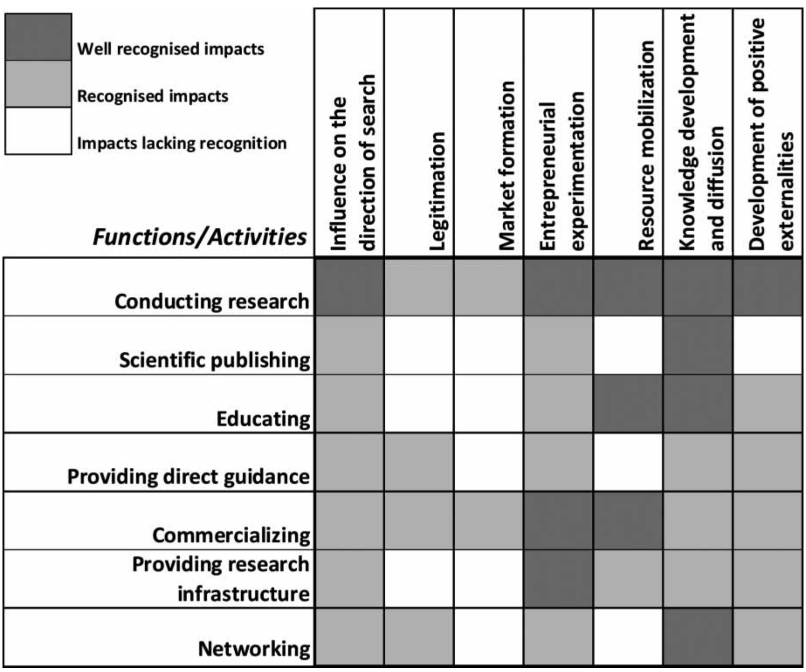

Figure 2. Mapping the direct impact of academic R&D on the functional dynamics of a TIS

impact knowledge diffusion (e.g. Mazzoleni and Nelson 2007; Meyer-Krahmer and Schmoch 1998) and may augment the capacity of non-academic actors to receive knowledge from outside sources (Mueller 2006). 'Contract research' develops knowledge mainly regarding specific problems (Gibbons and Johnston 1974; Mansfield and Lee 1996).

Second, 'scientific publishing' has a well recognised impact as a codified and open type of knowledge diffusion (e.g. Agrawal and Henderson 2002; Godin 1996; Lester 2005). Third, 'networking' has a well-recognised link to knowledge diffusion. The importance of informal contacts and face-to-face interaction is stressed (e.g. Faulkner and Senker 1994; Lester 2005; Meyer-Krahmer and Schmoch 1998; Molas-Gallart et al. 2002; Pavitt 1998). So is the role of networking activities in providing an entry into national and international networks of expertise and practice (Bonaccorsi and Piccaluga 1994; Salter and Martin 2001).

Fourth, 'educating human capital' is a channel of knowledge diffusion (e.g. Appleseed 2003; Mazzoleni and Nelson 2007; Pavitt 1998; Salter and Martin 2001), being 'the best form of technology transfer' (Lester 2005, 12). It provides knowledge about fundamental principles (Faulkner and Senker 1994; Salter et al. 2000) and augments receiver capacities (Arnold, Good, and Segerpalm 2008; Callon 1994; Gibbons and Johnston 1974).

'Resource mobilisation' has three well recognised points of impact. 'Conducting research activities' impacts resource mobilisation as high quality research attracts human and financial capital (Appleseed 2003; Pavitt 2000; Salter et al. 2000). Regarding the impact of 'educating', several studies on the economic impact of publicly funded research indicate the access to skilled graduates as the primary benefit to firms (e.g. Salter and Martin 2001; Schartinger, Schibany, and Gassler 2001). By having academic researchers train graduate and undergraduate students, as well as mid-careers and executives, capabilities relevant for the development of the TIS are mobilised (Jacobsson 2002; Mansfield 1995). This is the case both for technical and managerial positions (Mazzoleni 2005). 'Commercialisation' activities also have a well recognised impact on resource mobilisation. New firms may attract outside investments (Appleseed 2003) or potential faculty members (Lester 2005). Intellectual property trade may also create income (Molas-Gallart et al. 2002; Yusuf 2008).

'Entrepreneurial experimentation' has three well recognised points of impact. 'Conducting research' generates technological opportunities that open up for entrepreneurial experimentation (e.g. Mansfield 1991; Nelson 1986; Pavitt 1991); although perhaps with long time lags and including both direct and indirect routes (Klevorick et al. 1995; Lindholm Dahlstrand 2008). 'Commercialisation' activities: the creation of firms (e.g. Howells, Nedeva, and Georghiou 1998; Salter et al. 2000; Wright et al. 2008), patents and licences (Hughes 2006; Lester 2005) and the development of product, processes and services (Cohen, Nelson, and Walsh 2002; Mazzoleni and Nelson 2007; Rosenberg and Nelson 1994; Scott et al. 2001) impacts immediately on entrepreneurial experimentation. 'Providing research infrastructure' improves the opportunities for experimentation. The infrastructure may be physical (Bonaccorsi and Piccaluga 1994; Faulkner and Senker 1994; Molas-Gallart et al. 2002; Rosenberg and Nelson 1994), e.g. instruments, or immaterial, e.g. engineering design methods (Arnold, Good, and Segerpalm 2008; Cohen et al. 2002; Rosenberg 1992; Salter and Martin 2001).

In sum, the literature points to well recognised impacts from various activities on the dynamics of these three functions. These include but go much beyond the direct impact of 'commercialising' on 'entrepreneurial experimentation'. Indeed, we have not seen any study that suggests that this activity is dominant in terms of impact.

Turning to the functions 'influence on the direction of search', 'legitimation' and 'development of positive externalities', we can note that no less than an additional 17 out of 49 points of impact are recognised, or well recognised, in the literature.

'Influence on the direction of search' is affected by all seven activities. Below, we will touch upon five of these. 'Conducting research' enlarges the technological opportunity set, tests the feasibility of proposed solutions (Gibbons and Johnston 1974; Jacobsson 2002; Mohamad 2006) and may, therefore, influence the direction of industrial research agendas (Etzkowitz 1998; Faulkner and Senker 1994; Hörstedt 2000; Weck and Blomqvist 2008). 'Educating' creates 'avant-gardists' who search for future opportunities within university, industry and policy (Arnold, Good, and Segerpalm 2008; Faulkner and Senker 1994; Jacobsson 2002; Mazzoleni 2005).[22] The direction of search may also be influenced by academics participating in 'networking' activities together with industry, e.g. as in the 'Radio Club' in the area of digital mobile radio in Sweden (Arnold, Good, and Segerpalm 2008).

'Providing direct guidance', such as consultations and informal advisory work, may influence by suggesting alternative ways of tackling problems (Faulkner and Senker 1994; Gibbons and Johnston 1974). Academic research can also provide critical reflections, for example on institutional settings, thus guiding policy makers[23] in setting the regulatory framework of the TIS. Hence, academic participation in both policy and industry advisory boards can play a central role in the early phase of a TIS, as in the case of fuel cells in Singapore (Box 1). Finally, by creating spin-off companies, a 'commercialising' activity, academia may influence technical change and the direction of development in industry (Rosenberg and Nelson 1994).

Closely associated are the impacts of academic R&D on 'legitimation'. Academics often provide expert advice (sometimes as a member of an advocacy coalition) regarding the desirability of a new technology (providing direct guidance), which may impact on legitimation. A part of such assessments are analyses (conducting research) on risks, such as social or environmental hazards, related to various technologies (Salter et al. 2000).[24] 'Networking' may have a similar effect on legitimation by drawing attention to ongoing activities and potential at conferences and workshops (Lester 2005). An example of networking was the initiative of a group of Swedish academics to influence the process of legitimation for nanotechnology in Sweden, as described in Box 1. 'Commercialising', in the form of academic spin offs, may enhance the legitimacy of the technology. There are examples of individual new firms with strong links to academic high publishing 'stars' that legitimise an area and attract other firms (Zucker, Darby, and Brewer 1998).

'Development of positive externalities' is influenced by six activities. It is well recognised that the non-rival and non-excludable properties of the output of academics 'conducting research' augment productivity in industry by expanding the available pool of knowledge (e.g. Arrow 1962; Autant-Bernard 2001; Grupp 1996; Nelson 1959; Salter and Martin 2001). 'Providing direct guidance' through consulting (Hellsmark and Jacobsson 2009; Scott et al. 2001) may result in a strengthened 'diffusion of knowledge' as academic consultants pass on experience from one client to another.

'Collaborative research', 'networking', 'providing research infrastructure' and 'commercialisation' may impact by preparing the ground for positive externalities.[25] 'Collaborative research' may result in a build-up of trust and a reduction in conflict (Hellsmark and Jacobsson 2009; Walter et al. 2007). 'Networking' between different communities related to the innovation process may build up social capital (Salter et al. 2000). The case of nanotechnology in Sweden showed how academics through networking activities tried to build social cohesion among the actors (Box 1). 'Providing research infrastructure' may have a similar effect. Universities may act as facilitators in the development of positive externalities by providing meeting places (Jacobsson 2002). Advocating external use of laboratories and testing facilities may bring different actors together (Molas-Gallart 2002). Indeed, Lester (2005) argues that a key role of universities is to create links between disconnected actors (e.g. by creating on-campus fora). 'Commercialisation' may create

Box 1. The cases of nanotechnology in Sweden and fuel cells in Singapore

The Case of Nanotechnology in Sweden	The Case of Fuel Cells in Singapore
Nanotechnology in Sweden has a strong concentration to academic activities, with links to industry through the materials area. However, national coordination and political interest in the area has been lacking (Perez and Sandgren 2008). In 2000, the Swedish Nano-Network was created by academic actors in order to draw attention to the potential of nanotechnology (Fogelberg 2002). They conducted workshops, linking academia, government and research funding agencies, institutes and industry in order to create a national sense of identity for nanotechnology in Sweden. They also produced a strategy document with policy suggestions, laying the ground for a coordinated Swedish national nanotechnology initiative. The network took a proactive and central role in the formation of the TIS. However, policy actors did not respond to these initiatives (Fogelberg and Sandén 2008) and Sweden is now one of very few countries in the industrialized world that lacks a national initiative regarding nanotechnology. A lack of coordination between the two main research funding agencies resulted in the absence of a joint Swedish programme. In parallel, several bills suggesting such an initiative were rejected in Parliament. Taken jointly, this obstructed the process of legitimation and the development of the Swedish nanotechnology innovation system.	A large number of national and international actors are today active in the area of fuel cells in Singapore, even though the TIS is in an early phase of its development. Two local universities were the first actors in the country to conduct activities related to fuel cells in the mid 1990s. Nanyang Technological University (NTU) was one of them, housing a group of researchers that later formed the largest fuel cell research group in Singapore. This group is the most productive research group in terms of academic papers within the area of fuel cells in Singapore and built up a competence base that turned out to be an important support for early innovation system building activities. Researchers from this group conducted a great deal of networking activities, such as hosting conferences and seminars and providing direct guidance. In particular, the participation of two individuals from the NTU group in policy advisory boards, strategic panels and road-mapping exercises not only strengthened legitimation and influenced the direction of search of policy makers but also helped the government to build the institutional setting for the development of fuel cells in Singapore (Mohamad 2006).

an entrepreneurial academic milieu inducing more ‘entrepreneurial experimentation’ (Bramwell and Wolfe 2008; Lester 2005). Moreover, augmenting the number of actors in the TIS increases the chances for new combinations to arise (Carlsson 2003). By enhancing the opportunities for each firm to participate in further entrepreneurial experimentation, an enlargement of the actor base in the TIS paves the way for positive external economies.

The matrix revealed 12 points of impact lacking coverage, in particular (and as expected) regarding the function of ‘market formation’.[26] This could have several explanations. First, there might be an absence of impact. Second, the literature review may have missed some points of impact that are, in fact, covered. Third, there is a direct impact but the literature coverage is poor. Fourth, as previously noted, indirect effects are excluded in the matrix. Including such effects may mean that some of the ‘empty’ points in the matrix would be filled.

3.3. *Key observations on the impact of activities on functional dynamics*

The main observation is that the majority (37/49) of the points of impact are recognised, reflecting the multitude of ways in which academic R&D has been shown to be of use. Quite expectedly, the literature recognises the strong impact of academic R&D on the functions of ‘knowledge development and diffusion’, ‘resource mobilisation’ and ‘entrepreneurial experimentation’. Yet, a large number of points in the matrix involved three other functions: ‘influence on the direction of search’, ‘legitimation’ and ‘development of positive externalities’. These functions are less tangible and, therefore, less easy to observe. The impact on these functions is, therefore, less quantifiable than product related impacts; e.g. the impact of academic spin-offs on entrepreneurial experimentation. Yet, there are powerful examples from case studies demonstrating that these functions are central, particularly in the early phase of TIS development (Jacobsson and Bergek 2004; Mohamad 2006; Suurs 2009).

4. Endogenous and exogenous factors conditioning the impact of academic R&D on TIS dynamics

Having demonstrated the multitude of known impacts of academic R&D, we will now address how we may explain the size and nature of the eventual impacts on the dynamics of a specific TIS.

Academia is only one of several structural elements in a TIS and the ultimate impact of academic R&D is dependent on the nature and dynamics of the other elements. Additionally, internal dynamics is only part of the picture. There are exogenous factors interacting with internal processes, influencing the evolution of the TIS.[27] Hence, the driving forces and obstacles to TIS dynamics are both endogenous and exogenous (Sandén and Jonasson 2005) (see Figure 1). An endogenous driving force may be demand from a leading-edge customer whereas an exogenous could be the climate debate and accidents such as Chernobyl. These are examples of factors destabilising the dominant ‘regime’ (Raven 2006), opening up windows of opportunities for new TIS.

From the perspective of an emerging TIS, it is particularly vital to identify blocking mechanisms, i.e. factors that provide obstacles to the development of powerful functions.[28] An endogenous blocking mechanism may be, for instance, poorly developed learning and ‘political’ networks that limit ‘knowledge diffusion’ and ‘legitimation’. An exogenous blocking mechanism may come in the form of highly organised incumbents defending their investments and making sure that institutions continue to be aligned to the dominant technologies. Further blocking mechanisms may be traced to the emergence of other TIS that compete for space both in the market and in the political arena.

Hence, the strength of the functions, and their feedback to structural change, are not only influenced by other structural elements (in a positive or negative way) but the dynamics of the system are also shaped by factors exogenous to the TIS. It is these endogenous and exogenous driving forces and obstacles that together set the larger context which conditions the impact of academic R&D. In Box 2, we give two illustrative examples.

If the system has achieved a momentum, then we would expect it to have a well-developed capacity to demand and make use of academic R&D. This was the case of the transition from analogue to digital mobile telephony when Ericsson and Telia jointly articulated a demand for more ‘knowledge development’ and more PhDs (‘resource mobilisation’) in digital radio technology (Box 2). This demand was satisfied which contributed to the successful strategic use of this technological discontinuity by Ericsson (Arnold, Good, and Segerpalm 2008).

If system growth is impeded by powerful blocking mechanisms, we would not expect much to result from academic R&D, even if it is brilliantly performed. This was the case of the world leading thin film solar cell research conducted in Uppsala, Sweden (Box 2). This R&D led to the

Box 2. The Swedish cases of Solibro and Ericsson

The Case of Solibro	**The Case of Ericsson**
Research on thin film solar cells started at The Royal Institute of Technology (KTH) in Stockholm in the 1980s. Key researchers moved to Uppsala University in the 1990s and participated in forming Ångström Solar Centre in 1996. A plan for the commercialisation of the world class R&D results involved spinning off a firm and finding a Swedish industrial consortium that could add competence and capital. Yet, interest among Swedish actors was very low (Malmqvist 2000). Indeed, a representative from a leading electro-technical company publicly announced that they would never produce solar cells. After intervention from the highest political level, new discussions took place with leading Swedish industrialists (Malmqvist 2000). A spin-off company, Solibro AB, was founded in 2000 by four researchers and a small amount of capital was supplied by a group of firms and a pension fund. The firm began to operate in 2003. Although development money was supplied by the Swedish Energy Agency, there was little interest by the firms to become suppliers of solar cells (Bengtsson 2007). When funding was subsequently sought for up-scaling of the production technology and the building of a manufacturing plant, Solibro AB eventually had to enter into a joint venture with the German firm Q-cells, forming Solibro GmbH. Solibro GmbH invested SEK 500 million in a plant and started the production of cells in May 2008 (Alpman 2008). Solibro AB in Uppsala functions as a manufacturing development centre.	Ericsson had successfully positioned itself in the mobile telephony industry based on analogue electronics. It worked closely with the operator Telia which helped Ericsson not only with a vision of mobile communication as a mass market product but also with creating a large regional market by implementing the NMT standard together with operators in the Nordic countries and Holland. In the mid 1980s, Ericsson and Telia feared that the knowledge base in digital communication would be too small to support industry in the next generation mobile telephony, which they knew would be digital. Industry, academia and STU (Swedish Board for Technical Development) had intense consultations. As a response, the research programme 'Digital Communication' was started in 1987 building on earlier smaller programmes in digital radio technology. The programme combined scientific excellence with an orientation towards a broader knowledge field in which a small but expanding part of Swedish industry (otherwise dominated by mechanical engineering) articulated a need for PhDs with capabilities which could be employed to develop systems according to GSM standards. As fresh funding was made available, and an initial competence had earlier been built up, universities could quickly respond by expanding PhD education in this field. The subsequent supply of PhDs enabled Ericsson to take a lead in the discontinuity from analogue to digital mobile telephony systems (Arnold, Good and Segerpalm 2008).

formation of a spin-off company (Solibro) which required substantial funding to scale up production technology. However, it failed to attract the attention of Swedish industrialists. Although advanced in terms of 'knowledge development', the TIS for solar cell technology was blocked by powerful mechanisms that obstructed many of the functions including 'legitimation', 'influence on the direction of search' and 'resource mobilisation'. Eventually Solibro's technology came to be exploited by a German company, located in a dynamic TIS for solar cells.

As these examples demonstrate, the societal impact of academic R&D is conditioned by factors that may be beyond the reach of even the most entrepreneurial academic.[29] However, taking a longer time perspective might lead to a different conclusion. The time scale involved in the formation of a new TIS is extensive, i.e. it should be counted in decades rather than years (e.g. Carlsson and Jacobsson 1997; Grübler 1996; Jacobsson 1993). There are a number of time lags that jointly contribute to this long period of time. These include, at the simplest level, the lag between the initiation of R&D and effects in terms of published papers which may take half a decade (Crespi and Geuna 2008). Transforming academic results into commercial products takes additional years. Mansfield (1998) reports a lag of six years on average. Yet another time lag, usually much longer than five years, is the one between the formation of a spin-off and its eventual growth (Lindholm Dahlstrand 1997). Further time lags are involved for all the smaller and larger changes to be carried out before the structure of a new TIS has been built, and before appreciable effects can be seen in terms of growth (Fontenay and Carmel 2001; Van de Ven and Garud 1989).[30]

The long time scale not only suggests an inherent uncertainty of the eventual effects of academic R&D (Molas-Gallart et al. 2002) but opens up for 'indirect' ways in which academic R&D impacts on system dynamics. In two examples, we will show how the initial formation of capabilities ('resource mobilisation') had an impact, with a substantial time lag, on 'influence on the direction of search' and further 'resource mobilisation'.

In the case of digital radio technology (Box 2), the capacity of the Universities to respond to an articulation of demand for PhDs was the result of earlier smaller programmes in digital radio technology. As it takes decades to build a knowledge base and capabilities (i.e. 'resource mobilisation'), the later expansion would have been impossible without these programmes. This means that the early academic R&D in digital radio technology opened up a window of opportunity for policy by maintaining a broad knowledge base and made industry's call for extended capabilities in digital radio technology realistic. In this way, academia impacted on the system function 'influence on the direction of search'. This led to 'resource mobilisation' in the form of new PhDs which, in turn, had a significant effect on Ericsson's ability to take the lead in a technological discontinuity.

Another example is Mazzoleni's (2005) analysis of the impact of the establishment of *Escola de Minas* in Brazil in 1876 (Box 3) which illustrates not only the wide range of ways in which students and staff contributed to the formation of a Brazilian TIS for steel making, but also highlights the significant role of academic R&D in the provision of staff for local and federal bureaucracies. Hence, through the formation of capabilities, it was possible to design an intelligent policy which 'influenced the direction of search' in industry and 'mobilised resources' for building up a Brazilian steel industry. As in the previous example, this impact became visible only long after the establishment of the *Escola de Minas.*

These two examples illustrate that 'indirect' effects may be significant and that academic activities subsequently leading to future commercialisation go far beyond those that are currently focused on (e.g. creating new firms and patents). Indeed, they may involve activities which, initially, may well be judged to have very limited social usefulness.

5. Conclusions and discussion

The rationale behind this paper was a number of problems associated with the belief (1) of a poor utilisation of the outcome of academic R&D and (2) in academic spin-offs, patents and licences as key mechanisms for making science useful. The purpose was twofold: (i) to go some way towards developing an analytical framework to enable us to capture and explain, and thereby assess, the full effects of academic R&D on the dynamics of a TIS; and (ii) by applying parts of this framework to the received literature, ascertain whether the strong belief in commercialisation as the key mechanism for making science useful is warranted.

We enriched the TIS approach with a classification of activities sprung from academic R&D. We proceeded to conceptualise the effect of academic R&D as not only its immediate impact on the structure of a new TIS (strengthening the actor and technology base) but also on seven

Box 3. The case of Escola de Minas

The Case of Escola de Minas

The Escola de Minas in Brazil was established in 1876. Initially, the impact was poor, being limited to upgrading of existing small-scale forges in the region of Minas Gerais and to a smaller involvement in a handful of investment projects in new blast furnaces. However, after 1910, the Brazilian government pursued a policy of promoting the development of an advanced iron and steel industry by forming markets and providing financial resources to investors. At that point, the capabilities formed at the Escola came to good use in several ways.

First, the University supplied local and federal bureaucracies with technically competent staff. Many alumni participated directly in policy making as elected officials in the state and federal governments, or provided technical advice on government policies and legislation related to the country's mineral resources. Of course, with a background from the University, the alumni was able to carry to their public service a great appreciation for the importance of the iron and steel sector, and for the obstacles and opportunities confronting the domestic industry.

Second, many staff and alumni became investing partners in new firms, assumed technical and managerial positions, provided technical advice to firms and enabled links to foreign technology suppliers. Indeed, staff and alumni were central to key entrepreneurial experiments leading to the formation of the most important business enterprises of the period 1910–1930. These experiments led the industry in a technological direction that was different from that in the developed countries, using charcoal instead of coal or electricity, paving the way for a Brazilian technological leadership.

Third, the activities of the university generated a pool of technical competences that the industry could use when it entered a phase of sustained development and technological catching-up (Mazzoleni 2005).

functions of a TIS. Using the received literature, we illustrated the wide range of impacts that academic R&D may have on the dynamics of such a system by 'filling' in as many as 37 points in a 7×7 matrix, in which each activity can potentially be linked to each function.[31] Hence, we outlined a way of capturing the diversity in the channels through which academic research is made socially useful and the many types of effects accruing from academic research. Of particular interest were the impacts related to the less tangible processes in innovation systems: 'influence on the direction of search', 'legitimation' and 'development of positive externalities'.

For the time being, our approach is limited to assessing the 'direct' effects of an activity on a function but it is easy to understand that there may be indirect effects in the form of secondary and tertiary impacts. For instance, 'providing direct guidance' (activity) may impact on 'legitimation' of a new technology (function) which, in turn, may help change a regulatory framework (structure), opening up for 'market formation' (function). Indeed, as the Brazilian case of the steel industry and the Swedish case of digital electronics demonstrated, these indirect effects may be substantial, but only seen after a long period of time.

The realisation of these potential effects is, however, affected by many other factors than the activities of academics. These factors pertain to other structural elements in the TIS as well as to the external context of the TIS. Thus, an analysis of this wider context is necessary for understanding the impact of academic R&D and designing appropriate policies.

In terms of assessments of academic R&D, a possible way forward would be to evaluate the impact by its contribution to functional strength rather than to structural change and economic growth. We would then restrict the impact of factors that are beyond the influence of academic researchers. For instance, in the case of the development of nanotechnology in Sweden, academics attempted, through networking and the development of strategic policy suggestions, to strengthen the function 'legitimation' (Box 1). However, the impact of these activities on structural change remains to be seen, for reasons beyond the reach of academic researchers.

Focussing on functional dynamics may, to a degree, also handle the problem with the long time lags until we see the full impact of academic R&D. The conceptual framework using the 'functions' approach captures changes in functional patterns before structural changes appear. Impact on functional dynamics may, therefore, be perceived as signals of future (potential) structural changes (Sandén et al. 2008). Yet, given the long time scale and the many indirect effects of academic R&D, we will probably always have to live with incomplete assessments.

The second purpose was to critically reflect on the belief in the central role of commercialisation in making science useful. As demonstrated in Figure 2, commercialisation impacted on all functions and is, thus, a powerful activity. However, the main message from applying the framework to the received literature is the great diversity of the types of impact of academic R&D, going far beyond those connected to commercialisation. Hence, the number and growth of academic spin-offs or number of patents and licences as impact indicators cover just a part of the full impact of academic R&D.

Clearly therefore, the strong belief in Europe may be perceived as uninformed. This suggests not only a possible failure in the receiver competence of policy makers but also that the belief in the poor utilisation of the outcome of academic R&D may be questioned – after all, how many of the points of impact have been studied empirically and using which time scale?

By developing and applying this framework, we have presented evidence that could lay the ground for both a more informed policy debate on the impact of academic R&D and for further scientific work.[32] With respect to the former, we are keen to emphasise that an inappropriate conceptualisation of how academic R&D impacts on society may lead to misguided policies.[33] With respect to the latter, we suggest three lines of enquiries. First, the literature used to 'fill' the matrix may be extended through additional literature reviews. Second, the proposed analytical framework could be applied to specific TIS, e.g. the one centred on 'green' nanotechnology, in order to explore its usefulness. Third, whereas the focus in this paper has been (largely) on the direct effects of academic R&D, we have pointed to both the existence of indirect effects (secondary and tertiary) and feedback processes between functions and structure, leading eventually to the formation and growth of a TIS. It would be useful to incorporate such indirect effects and feedback processes into case studies. Although these would need to span over an extensive time period, they would be able to provide a more complete picture of how science is made socially useful. Such studies may also shed light on the opportunities and limits of academics as system builders.

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Notes

1. This view is also shared by individual member states. A case in point is the Swedish Government (Regeringen 2005, 140) which recently wrote that: 'The investments in research give, however, insufficient results in the form of economic growth … knowledge transfer to industry and commercialisation of research results need to be increased'.

2. The effects of academic R&D do not solely come in the form of benefits. This paper does not provide a framework to evaluate these effects in terms of their desirability, but simply to trace them.
3. We will refer to case studies (summarised in Boxes) that illustrate some of our arguments. These case studies are inserted for pedagogical reasons and vary a great deal with respect to technologies and countries studied. They constitute, however, neither the empirical base for generating the framework nor a 'proof' of its validity. Further work needs to be undertaken to apply the framework to specific technologies.
4. This section draws heavily on previous work carried out by one of the authors (e.g. Bergek et al. 2008; Bergek, Jacobsson, and Sandén 2008).
5. Knowledge value collectives are a conceptualisation of these type of networks, where knowledge generation and use is captured and valued as an embedded process in social networks and communities (Bozeman and Rogers 2001, 2002; Rogers and Bozeman 2001).
6. The sociological and entrepreneurship literatures point also to the importance of social networks (Geels and Schot 2008; Johannisson 2000). Networks between artefacts may also be included.
7. This framework has been developed in a number of steps with recent contributions by Hekkert et al. (2007), Bergek et al. (2008) and Bergek, Jacobsson, and Sandén (2008).
8. We will give two additional examples of overlaps. First, resource mobilisation is a feature of all the functions but we choose, nevertheless, to label one function 'resource mobilisation'. In that function, we focus on mobilisation of specialised capabilities and capital since this represents a generic problem in the formation of a new TIS. Second, there is an overlap between 'knowledge development and diffusion' and 'entrepreneurial experimentation'. In the context of this paper, the function 'knowledge development and diffusion' refers more to formal knowledge coming out of academic and industrial R&D than to the more applied knowledge generated by entrepreneurial experiments.
9. Whereas Porter focuses more on opportunities for larger firms to strengthen clusters, Van de Ven's (1993, 218) perspective is that of the entrepreneurial firm and the development of an 'infrastructure' for entrepreneurship: 'The basic argument underlying the framework is that while the industrial infrastructure facilitates and constrains efforts of individual entrepreneurs, it is the entrepreneur who constructs and changes the infrastructure. Thus, we view the infrastructure at the macro-community level as grounded in a theory of action at the micro-level of individual entrepreneurs in private firms, government bureaus, research institutes, or various trade associations'.
10. Of course, in the evolution of a TIS, there is much tension and conflicting views as to how technology and markets should develop. Firms have different competencies and visions of the future and compete in terms of different design approaches. As explained in the text under 'entrepreneurial experimentation' in Table 1, such a variety is very useful as it handles uncertainty from a social perspective.
11. These actions may be linked to the concept of translation (actors attempting to build up a new world) presented in actor-network theory (e.g. Callon 1986, 2001; Latour 1987).
12. These functions may be thought to be far removed from the role of academia but in Section 3.2 we will demonstrate that this is not the case, with the exception of 'market formation'.
13. Suurs (2009) identifies a 'Science and Technology Push motor' which is one out of several forms of cumulative causation in an early phase of system development. In this motor, academia has a strong impact on policy by formulating expectations of a new technology. In the case of fuel cells, for instance, Suurs (2009, 214) argues that: 'The *STP Motor* turned an idea which was radical at first into one widely shared among policy makers and (some) entrepreneurs. In terms of institutions, this affected the cognitive rule set of actors. For the HyF case, the vision was to establish a Dutch fuel cell industry by targeting the MCFC technology'.
14. The functions constitute elements of an analytical framework which helps us make sense of the world but they are not parts of a model in an engineering sense. Agency is always central to social science. This means that functional dynamics form some of the context for human choice but do not determine it. For instance, a strong process of legitimation may impact on, say, legislation but does not determine it. Nor do the functions explain the process of forming networks, although they explain some of the conditions that may influence the choice of actors to participate in networks (e.g. market formation opens up for user–supplier networks and knowledge formation at Universities opens up for university–industry networks). The causal links between functions and structure are, thus, not deterministic ones but refer rather to probable ones.
15. Our focus on the effects of academic R&D does not mean that we adhere to the linear model of technical change. As is evident from our discussion above, we see technical change as a process involving many linkages and feedbacks (Kline and Rosenberg 1986).
16. Our focus on activities is strengthened by two additional arguments. First, the expression of 'outcome' or 'product' may imply a one-to-one relation between activity and outcome. An activity may, however, create impacts that go beyond one sole 'outcome' (Faulkner and Senker 1995). Second, some of these activities, 'providing direct guidance', may not be captured with a 'product' perspective.

17. Activities, such as training human capital or commercialising, might be seen as separate from the process of carrying out research. However, these activities are not isolated but interconnected. In order to provide effective training, teaching needs to be closely linked to research.
18. Only a smaller part of the received literature used the same terms as in our framework of 'functions of innovation systems'. Hence in most cases, we have interpreted the terms in literature into functional terms.
19. Examples of keywords were: impact, academic R&D, research assessment, effects, university–industry relationships, societal impact, and innovation system. The main search engine used was Science Direct. Other engines were JSTOR and the Chalmers University of Technology library databases.
20. It is reproduced in a longer electronic version of the paper which the interested reader can access from the authors. In Appendix II of that paper, references are given for each point of impact. A range of methodological challenges and how these were handled is also described in that appendix.
21. An additional eight points of impact on these functions are 'recognised' but these will not be commented on for reasons of space.
22. As 'avant-gardists' in a new area, the human capital may, in turn, attract more human capital (Arnold, Good, and Segerpalm 2008).
23. Thus, academia may influence the direction of search of policy makers.
24. Faulkner and Senker (1995) stress another aspect of impact; in their use of new instrumentation, academia may legitimate a specific technological solution. Academia's use of products in their research may also improve a corporate image in the role of prominent research suppliers (Bonaccorsi and Piccaluga 1994).
25. In addition, Geiger and Sá (2008) argues that educating graduate students may help to build networks between university and industry, thus paving the way for external economies.
26. However, when 'conducting research', some impact is recognised. By acting as an innovative customer, even when conducting intra-academic research, universities can contribute to the formation of markets (Jacobsson 2002; von Hippel 1976). Also, 'commercialising', through innovative start-ups or products, may create new markets (Mueller 2006).
27. Strategic niche management (Kemp, Schot, and Hoogma 1998) conceptualises the technology-specific elements as a 'niche' and refers to 'niche-internal' processes and to the more general elements as 'regimes' and 'landscape'. The interplay between the 'niche' and the regime (roughly sector, e.g. the agricultural sector) is a central part of the evolutionary process.
28. See Jacobsson and Johnson (2000), Unruh (2000) and Jacobsson and Bergek (2004).
29. Hellsmark and Jacobsson (2009) relate the story of a 'system builder' for gasified biomass in Austria, Professor Hofbauer, who has managed to positively affect six of the functions, but the seventh, market formation, was beyond his reach as it involved changing the national regulatory framework for the power sector.
30. The development of mobile telephony is an example of this where the fundamental principles were already known during the 1940s, but the larger impact on growth did not materialise until the 1990s (Arnold, Good, and Segerpalm 2008).
31. These figures should not be seen as exact ones given the methodological challenges referred to in Section 2.2. See also footnote 20.
32. See Dosi, Llerena and Labini (2006) for a very useful critique of the notion of a European paradox and Jacobsson and Rickne (2004) for a critical assessment of the belief that Swedish academic R&D accounts for a much higher share of gross domestic product than in other OECD countries.
33. For instance, since the performance of one activity, say creation of spin-offs, is likely to come at the expense of another, given a limited set of resources held by academia (Cohen, Nelson and Walsh 2002; Yusuf 2008), a policy induced focus on this activity is likely to have unintended consequences. A more appropriate conceptualisation of how science is made socially useful would, hopefully, reduce the risks of such unintended consequences.

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The influence of academic R&D on the commercialization of nanotechnology in Sweden

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Abstract

Nanotechnology has received much attention as a source of opportunities for generating economic growth. However, the challenges for commercializing nanotechnology are many. This paper identifies a number of these by analysing how academic R&D has influenced the commercialization of nanotechnology in Sweden. The utilized analytical framework centres on the impact of academic R&D on a set of key processes in the industrialisation of a new technology. The analysis reveals many direct ways in which academia has influenced commercialization, but also a whole range of indirect ways, such as 'influencing the direction of search' of actors into the system, enhancing the 'legitimation' of the field and paving the way for commercialization through knowledge development and formation of human capital. This impact is, however, constrained by a set of blocking mechanisms. Policy may enhance commercialization by addressing these, for example by supporting knowledge development on potential environmental and health risks, facilitating the formation of nursing markets and funding verification and scaling up of production.

1. Introduction

In the last decade, nanotechnology has received much attention as a source of opportunities for generating economic growth and other societal benefits. However, as with other generic technologies, the challenges for commercializing nanotechnology are many (Swedish Government, 2008). Identifying and addressing these challenges is, therefore, of critical importance.

As nanotechnology is a science based field where academic researchers are significant actors (Fogelberg and Glimell, 2003), attention has to be given to the influence of academic R&D on the commercialization of nanotechnology. Conventionally, addressing this issue is limited to enquiring about the role of academics in starting up new firms, applying for patents and licensing these, i.e. direct and easy to measure ways in which an impact is seen (Swedish Government, 2008; European Commission, 2007).[1]

However, as is firmly established in the science policy literature, academic R&D influences commercialization in a multitude of ways (e.g. Salter and Martin, 2001). For instance, academics may influence the design of policy programs with the purpose of forming early markets or they may act as consultants to industry with respect to which application the firm should, or should not, put emphasis on. A holistic perspective is, therefore, needed if we are to capture the influence of academic R&D on commercialization (Arnold, 2004; Martin and Tang, 2007).

The analytical framework 'technological innovation system' (TIS) provides such a holistic perspective (e.g. Carlsson et al., 2002; Bergek et al., 2008 and 2010). A TIS is an innovation system with a boundary defined by the technology in focus, be it nanotechnology, biomaterials or off-shore wind power. The commercialization of a technology can be understood as the growth of such a system and

[1] The Bayh-Dole act is another example of policy's focus on such impacts.

the influence of academic R&D on the commercialization of a new technology may, consequently, be studied as its impact on system growth.

Hellsmark and Jacobsson (2009), Mohamad (2008) and Suurs (2009) were the first attempts to use the TIS framework to capture the effects of academic R&D on system growth. They demonstrated the importance of many subtle, and difficult to measure, impacts that are required to be understood if we are to truly capture the influence of academic R&D on the commercialization of a new technology. They also informed about the multitude of contextual factors that may reduce the extent of this influence. An extensive literature review (Jacobsson and Perez Vico, 2010) generalised these findings and further developed the framework as a tool to systematically capture and explain the effects of academic R&D on the dynamics of a TIS.

The purpose of this paper is to analyse how academic R&D has influenced the commercialization of nanotechnology in Sweden by assessing its impact on the growth of the Swedish nanotechnological innovation system. The analysis includes identifying obstacles that reduce this influence and how it can be enhanced by further policy intervention. Section 2 briefly describes the framework.[2] The framework is applied in sections 3 and 4 whereas section 5 contains our main conclusions.

2. Analytical framework and a note on methodology

A technological innovation system (TIS) includes four structural elements. *Actors* are individuals, firms, universities and other public as well as non-governmental organisations. The *technology* is embedded in artefacts (e.g. equipment), coded knowledge (e.g. patents, scientific papers) and in individuals' knowledge. *Networks* are made up by relations between actors in the system. These may come in the form of learning networks (e.g. user-supplier, university-industry) and political networks. *Institutions* refer to laws, regulations, norms and culture that set the 'rules of the game'. These structural elements influence one another, making up the structural dynamics of the TIS. As an

[2] For a more extensive treatment, please see Bergek et al, 2008 and 2010.

example, a group of actors can create a political network that influences regulations in favour of commercializing a technology. In turn, this may attract more actors and the system structure builds up.

To understand what drives structural dynamics of a TIS, it is useful to utilize an analytical scheme of key processes, labelled functions, in the industrialisation of a new technology (Bergek et al., 2008). These processes are extracted from the literature and constitute a synthesis of perspectives on industrialisation in disciplines such as evolutionary economics, economics of innovation and organisational sciences. For instance, legitimation is a key process in that legitimacy is required to get access to markets and capital as well as for actors to acquire a political strength. Table 1 summarizes these processes.

Table 1 Functions of technological innovation systems (Jacobsson and Perez Vico, 2010)

Functions		Content of the functions
Influence on the direction of search	is the process by which	actors are induced and/or pressured to enter the technological field or to choose a particular line of development within the field. For a TIS to be formed, new actors have to populate it. The system as a whole also needs to generate variety in terms of technologies, applications and markets as well as exploring this variety. Incentives may come in the form of visions, expectations of growth potential, regulation and policy, articulation of demand from leading customers, technical bottlenecks, crises in current business, etc.
Legitimation	is the process by which	the legitimacy of the new technology and industry is strengthened through socio-political actions by various organisations and individuals. Gaining legitimacy implies overcoming the liability of newness. An acceptance as a desirable technology/industry by relevant actors is necessary for the mobilization of resources, for demand to form and for actors to acquire political strength. Central elements are alignment of institutions, beliefs and expectations from actors and the public.
Market formation	is the process by which	customers articulate their demand and markets develop through various stages, i.e. "nursing" or niche markets (e.g. in the form of demonstration projects), bridging markets and eventually mass markets.
Entrepreneurial experimentation	is the process by which	new opportunities and knowledge of a tacit, explorative, applied and more varied nature are developed through the testing of new technologies, applications and markets. A variety of experiments creates a pool of options that helps the TIS meet inherent uncertainties. The experimentation includes the development and investments in artefacts such as products, production plants and physical infrastructure (i.e. the materialisation of new technology). Materialisation gives concrete manifestations of the opportunities that the technology presents, which may also strengthen 'legitimation', since concrete applications may raise awareness among actors of the opportunities of the technology.
Resource	is the process	actors raise financial and human capital as well as complementary assets. In

mobilisation	by which	an early phase of TIS development, the sourcing of specialised capabilities and capital represents a generic problem.
Knowledge development and diffusion	is the process by which	knowledge is developed, diffused and combined in the system, thereby increasing the breadth and/or depth of the knowledge base.
Development of positive externalities	is the process by which	the collective dimension of the innovation diffusion process emerges, through the development of "free utilities" (i.e. when investments by one firm benefit other firms 'free of charge'). It indicates the dynamics of the system since externalities magnify the strength of the other functions. As the system grows, positive externalities may flow as a consequence of, for instance, resolution of uncertainties, emergence of pooled labour markets and a strengthened process of legitimation. An aspect of this function is the build-up of networks and the socio-cultural capital that links the actors in the TIS and paves the way for reciprocal external economies. This community building may take place when a common geographic and technological frontier, or a shared background, can be identified. Actors may then see themselves as a part of a system, with common problems and opportunities, and can grasp the importance of collective action.

The functions are affected by the structural elements of the TIS, as well as by factors exogenous to the TIS. For instance, 'influencing the direction of search' of firms to a new TIS centred on solar cells may be affected by e.g. the articulated demand from leading edge customers (actor, structure), policies promoting the diffusion of solar cells (institution, structure) as well as the climate change debate (exogenous factor).

As key processes in the industrialisation of a new technology, the functions have in turn a strong bearing on the structural build-up of the system. For instance, a powerful process 'influencing the direction of search' (function) will induce firms to enter into the system (structure) and a powerful process of 'legitimation' (function) may help align institutions (structure) to the new technology.

These links between structural elements and functions make up the dynamics of the TIS. For instance, the creation of a clean room for research in nanotechnology (structure) facilitates entrepreneurial experimentation (function). This may eventually create actors in the form of spin offs (structure) that mobilize resources by attracting new capital (function), and so the system structure builds up.

System dynamics may, of course, be described in functional or structural terms, or both. The functions approach focus on the actual achievements in the system, i.e. how well it works, rather than on the structural dynamics, i.e. what components it contains. In what follows, we will focus on system dynamics in functional terms. This allows us to identify system weaknesses in the form of poorly performing functions obstructing the performance of the system. These system weaknesses may be explained by specific blocking mechanisms. For instance, a perceived high health or environmental risk of applying nanotechnology in a specific area may be a blocking mechanism for 'entrepreneurial experimentation' as well as for 'legitimation'. System weaknesses and the associated blocking mechanisms may, therefore, act as guides to policy actors with an ambition to intervene in the TIS in order to strengthen the commercialization of a technology.

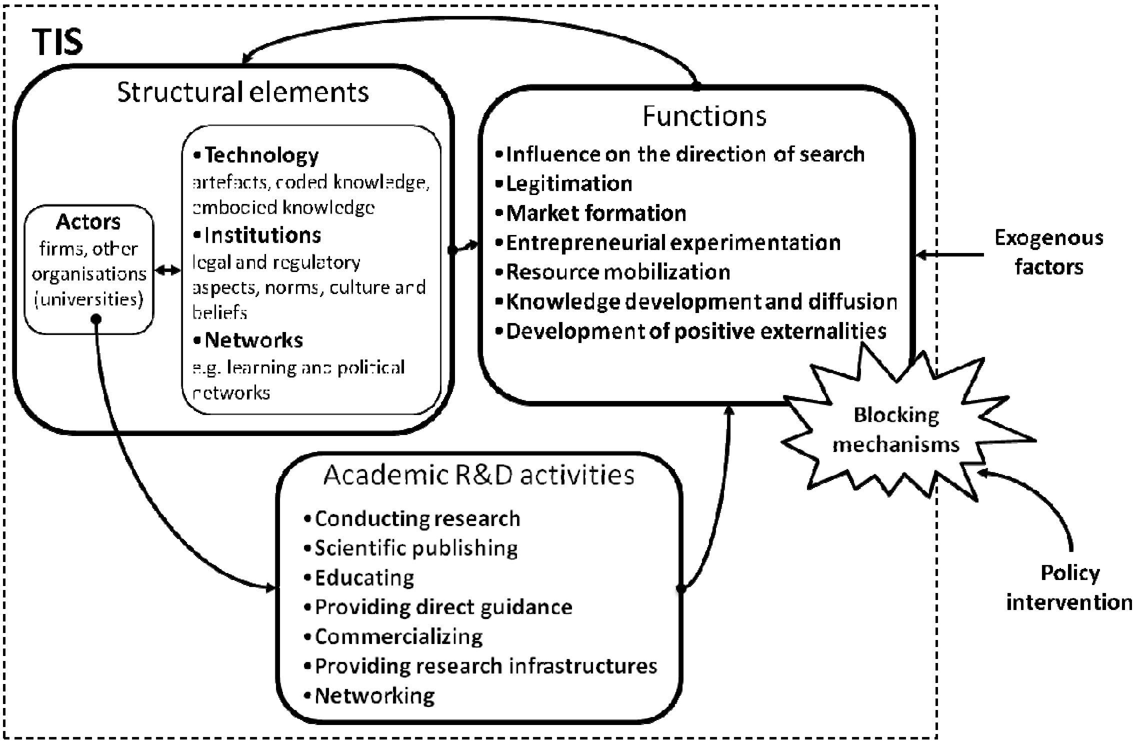
The focus of this paper is on the impact of a specific actor, the academic researcher, on the commercialization of nanotechnology in Sweden and how policy may intervene to enhance this impact. A starting point in the analysis is a specification of a set of activities pursued by academic researchers. These are listed in Table 2. A combination of these activities constitutes the everyday life of academics. Each of these activities may impact on one or several functions.

Table 2 Activities embedded within or sprung from academic research and development (Jacobsson and Perez Vico, 2010)

Activity	Description of the activity
Conducting research	Many combinations of research set-ups regarding conduct, funding and commissioning are possible. Examples are *joint research and development projects* (academic researchers cooperate with non-academic actors), *contract research* (conducted by academia, but commissioned and financed by industry/policy) and *intra-academic research*.
Scientific publishing	This refers to the academic world's traditional formal form of diffusing information, including publishing scientific *papers*, *books* and *reports*.
Educating	Academia educates *undergraduate*, *MSc, PhD* and *executive education students.* Specially designed courses for industry or policy making bodies may be provided in the form of privately arranged *contract training* or government sponsored *collaborative training*. These may be combined in the case of *industrial PhDs*.
Providing direct guidance	Industry or policy actors receive guidance from academia through *participation in advisory boards*, *informal advisory work, consultations* or when academics participate in *public discussion and debate*. Examples of the latter are non-scientific publications and articles, media appearances, public presentations and seminars. Often, direct guidance does not require new research, but could not be carried out without a close link to research. Guidance is not restricted to natural science and engineering knowledge but include providing guidance to society at large, such as on social and economic issues connected to technical choices, as

	well as providing frameworks and empirical underpinnings of policy.
Commercializing[3]	Commercialization activities refers to the direct processes of *creating new firms*, *patents* and *licences*, as well as those creating *products, processes and services* excluding patent or licence agreements.
Providing research infrastructure	Conducting research drives investments in *physical facilities*, like laboratories or clean rooms and libraries. The research activity itself develops the infrastructure as it formulates the needs and uses of it. Industry or government actors may then utilize this infrastructure. Infrastructure may also consist of *instruments*, *engineering design and methods*, as well as *methods of doing research*.
Networking	The *creation* and *maintenance* of networks is an integrated part of academic activities. It is purposefully performed by academia to facilitate other activities. Formal and informal networks connect academics to national and international groups of actors. Organising and participating in academic and non-academic conferences and seminars is a key activity.

These activities are incorporated in a model of structural and functional dynamics of a TIS, see Figure 1. Below, we will a) map these activities and trace how they impact on the seven functions b) identify a set of blocking mechanisms that obstruct this impact and c) point to key problems that policy has to address.



[3] This activity strictly refers to direct commercialization activities conducted by academia. As is evident from the text, other activities indirectly influence the commercialization process of the technology.

Figure 1: A model of structural and functional dynamics of a TIS, adopted from Jacobsson and Perez Vico (2010)

However, before we proceed, some remarks on the empirics will be made. The main author has observed the Swedish nanotechnology TIS since 2006 in her capacity as a policy analyst at the Swedish Governmental Agency for Innovation Systems. In that capacity, she has participated in the OECD Working Party on Nanotechnology since 2007 and was head analyst in the Swedish Government efforts to develop a Strategy for Nanotechnology in 2009. Engagement in national and international workshops, hearings and conferences allowed her to gain much insight into the TIS. This insight is of particular importance given the many subtle and difficult to measure influences that academics may have on system dynamics. Additionally, data was collected from semi-structured interviews and secondary sources. 35 interviews with key members of the TIS were conducted. 18 of these were with leading researchers. Secondary data, such as found in reports, books, scientific articles and Swedish media was, of course, also reviewed.

3. Tracing the influence of academic R&D on the functions

In this section, we map the activities identified in table 2 and trace how they impact on the seven functions in the Swedish nanotechnological innovation system.[4] We will first describe the activities and then analyse their impact.

Conducting research is fundamental since the other activities depend on a close connection to high quality research (Hultman, 2009; Olsson, 2009; Willander, 2009). Indeed, almost all universities in Sweden conduct high quality nanoscience research (Swedish Research Council, 2005). Whereas some researchers focus on methodology development and fundamental principles, others are application oriented and directly linked to established industries or to own ventures (e.g. Kasemo, 2009; Olsson, 2009; Willander, 2009).

[4] For reasons of space, only a selection of identified activities is given.

Swedish researchers account for 1.5 per cent of nanotechnology *scientific publications* (ISI Web of Science, 2008)[5] which is the same share as for all scientific articles (OECD, 2007). This means that Sweden has no specific focus on nanotechnology. However, as Swedish academics publish extensively, there is a substantial volume of publications, given the size of the country (Jacobsson and Rickne, 2004).[6]

Nanotechnology *educational* activities centre on PhD students, where the link to R&D is particularly important (e.g. Edström, 2009; Olsson, 2009). There is less activity at the undergraduate or Master levels, although an MSc program in Nanotechnology is running at Lund University. Nanotechnology researchers also provide input into programs not directly aimed at, but related to, nanotechnology (Edström, 2009). Finally, firms receive informal education when utilizing clean rooms (Bengtsson, 2006; Montelius, 2006).

Researchers *provide direct guidance* to industry and policy (e.g. Delsing, 2009; Hultman, 2009). In terms of established industry, guidance appears mainly through informal consultations in the context of stable university-industry networks. Participation in boards of academic spin-offs is common, although informal guidance is also a natural continuation of the spin-off process (e.g. Andersson, 2008; Samuelson, 2009). Researchers also participate in policy advisory boards and represent policy makers in international activities (Kasemo, 2009; Sandén, 2008).

In terms of direct *commercialization*, three out of four Swedish companies with operations built around nanotechnology are university spin-offs (Dahlöf and Wihed, 2010). A quarter of the Swedish nanotechnology patents were related to university researchers in 2004 (Meyer, 2005b). Compared to the national level, this is a high share (Lissoni et al., 2007).[7] As for product developments, Linköping

[5] The data is for 1997-2007 using the search string by Meyer (2005a).

[6] The absolute numbers of published nanotechnology articles place Sweden on level with countries like Israel and Brazil (Lux Research Inc., 2009).

[7] Lissoni et al. (2007) showed that 6% of Swedish EPO patents issued between 1994 and 2001 had an academic inventor. Meyer's (2005b) data from 1991 to 2004 includes EPO and USPTO patents. Differences in methods

University played a critical role in product developments refining the Max-fas material (e.g. Hultman, 2009; Liljenberg, 2008).

The *Provision of research infrastructure*, such as instrumentation and access to clean rooms, is of particular importance in nanotechnology research (Andersson, 2008). Swedish researchers develop instrumentation for industry and academia (Olsson, 2009; Swedish Research Council, 2005). The provision of research and engineering designs and methods, carried out by many of the researchers, pushes research frontiers (Olsson, 2009). Larger clear rooms exist at four Universities.

Networking is purposefully performed by academia. Some researchers focus on developing international research networks, others on networks with industry. A Swedish nanotechnology network was created in 2000 and took a proactive role in networking, but has currently no activity (Fogelberg, 2002; Johansson, 2006). The university founded company Pronano attempted to create networks between industry and researchers at Lund University. Industrial interest was, however, lukewarm and the company fizzled out (Magnusson, 2009).

Having outlined the range of activities pursued by academic researchers, we will now discuss how these influence the seven key processes in the formation and growth of the Swedish nanotechnological innovation system. The discussion will be organised in terms of the matrix found in Figure 2.[8] The matrix demonstrates, in a simple manner, the multitude of ways in which academic R&D impacts on system dynamics. In what follows, we will discuss how each function is affected by various activities pursued by academic researchers.

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and data sets rule out a direct comparison, but the data indicates that the contribution to patenting amongst nanotechnology researchers is high.

[8] For a point in the matrix to be shaded, only one observation was required. A large number of observations were made in the interviews and detected in secondary material but for reasons of space, we will only provide selected examples.

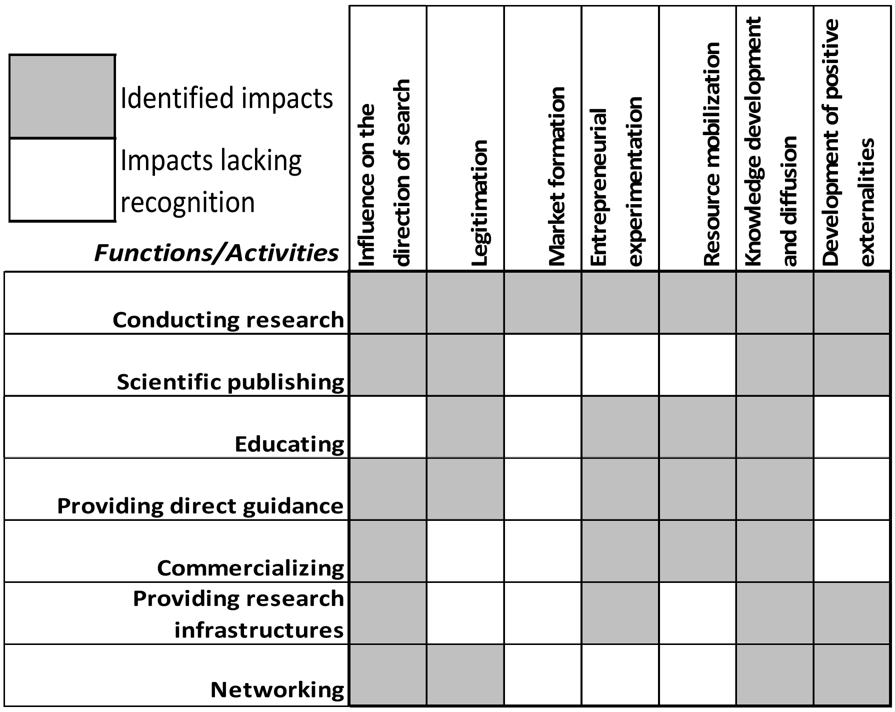

Figure 2: Impact of academic R&D on the functions in the Swedish nanotechnological innovation system.

Six of the activities have a bearing on the process ***Influence on the direction of search***. *Conducting* exploratory *research* in single-electron transistors at Chalmers University of Technology fundamentally influenced the development direction of quantum computers, guiding the research community (e.g. Swedish Research Council, 2005). A part of this process is *Scientific publishing* which provides quality assurance through peer review and identifies possible pitfalls in the development of nanotechnology (Hultman, 2009). As for *provision of direct guidance*, input from researchers into the design of three ground-setting nanotechnology research programs was central (Fogelberg, 2002; Kasemo, 2009; Weinberger, 1997).[9] As mentioned above, formal and informal consultations are made with industry (Hultman, 2009; Liljenberg, 2008) and guidance is also provided by participating in the public debate (e.g. Kasemo, 2009; Sandén, 2008). *Commercialization* activities undertaken by Linköping University researchers together with industry influenced the research agenda of involved companies (Reineck, 2008). Providing *research infrastructures* in the form of new instrumentation,

[9] The development of the national strategy for nanotechnology in 2009 was greatly influenced by guidance activities from a group of researchers at Chalmers University of Technology and Gothenburg University (Svendsen, 2010).

opens up for new areas of research (Olsson, 2009). Through *networking* activities, such as the Swedish Nano Network, researchers worked to politically influence the national research agenda (Fogelberg, 2002; Johansson, 2006).

The process of ***Legitimation*** is also influenced by many activities. *Conducting* internationally recognized *research* creates legitimacy for the national TIS and for specific actors (Delsing, 2009; Samuelson, 2009, Andersson, 2008). Successful *scientific publishing* also legitimates the Swedish TIS (Hultman, 2009; Kasemo, 2009). Regarding *educating,* an internationally recognized MSc in Nanotechnology in Lund legitimates the creation of human capital in Sweden (Samuelson, 2009). *Providing direct guidance* impacts on legitimation through researchers' participation in policy bodies and in public debates (Kasemo, 2009; Sandén, 2008). *Networking* activities by the Swedish nanotechnology network brought attention to and legitimated the area (Fogelberg, 2002; Johansson, 2006).

The only way in which ***Market formation*** is influenced is through *conducting research*. Researchers need to access instruments in their research, creating a market and providing input to instrument developers (Olsson, 2009).

As many as five activities influence the process of ***Entrepreneurial experimentation***. Knowledge generated from *conducting research* has resulted in a large number of academic spin-offs (Dahlöf and Wihed, 2010)[10]. Some of these are founded by PhD students which illustrates the influence of *education* on the function (Andersson, 2008). A surface physics and chemistry research program contributed to entrepreneurial activities amongst industrial partners, like the establishment of a car catalyst plant (Weinberger, 1997). An example of how *providing direct guidance* influenced entrepreneurial experimentation is Professor Bengt Kasemo's consultations with the company Nobel Pharma, leading to the development of dental implants (Weinberger, 1997). *Commercializing* in the

[10] This impact relates to companies founded on knowledge generated by academic research, not necessarily meaning that academics themselves have started the company.

form of patenting is essential for undertaking entrepreneurial experiments (Hultman, 2009; Samuelson, 2009). *Provision of research infrastructures*, such as access to university clean rooms and instrumentation, is vital for entrepreneurial experimentation, especially for spin-off companies (e.g. Ljungcrantz, 2008; Swedish Research Council, 2002).

Resource mobilization is impacted by four activities. *Conducting* high-quality *research* attracts international capital to Sweden (Willander, 2009). Industrial actors point out *Educating* as central for mobilization of human resources (e.g. Liljenberg, 2008; Ljungcrantz, 2008). The impact of *provision of direct guidance* can be exemplified by the input given by researchers into the design of three ground-setting nanotechnology research programs that mobilized substantial resources for the area (Fogelberg, 2002). Regarding *commercializing*, academic spin-offs, patents and participation in product developments can generate revenues, although this has been modest so far (Dahlöf and Wihed, 2010; Perez and Sandgren, 2008).

All activities influence ***Knowledge development and diffusion***. *Conducting research* creates a strong Swedish knowledge base in nanosciences (Swedish Research Council, 2005; Weinberger, 1997). Several high *publishing* researchers can be found in Sweden (Meyer, 2005a). Patents and publications are strongly linked, indicating knowledge diffusion between researchers and industry (Meyer, 2005b). Regarding *education*, PhD's are pointed out as the best form of knowledge diffusion (Hultman, 2009; Kasemo, 2009). *Providing direct guidance* impacts on knowledge diffusion through consultations with firms (Liljenberg, 2008; Ljungcrantz, 2008). *Commercializing* through academic patenting induces knowledge diffusion (Meyer, 2005b). *Providing research infrastructures,* like instrumentation, is essential for nanotechnology knowledge development (Fogelberg, 2002; Swedish Research Council, 2005). International *networking* provides channels for absorbing knowledge generated abroad (Olsson, 2009; Willander, 2009). Finally, academic researchers act as gate-keepers to research communities for companies (Liljenberg, 2008; Reineck, 2008).

Four activities impact on the process of ***Development of positive externalities***. Experimentalists, theorists and engineers in different scientific fields interact and communicate in the TIS. The complementarities in their *research* are a central aspect of the TIS (Fogelberg, 2002; Olsson, 2009). Apart from generating classical information based externalities, *scientific publishing* has a signalling effect facilitating network creation, which is central to this function (Weinberger, 1997). The *provision of research infrastructures* sets the ground for positive externalities, since sharing facilities and equipment creates networks and social cohesion between companies and universities (e.g. Samuelson, 2009; Swedish Research Council, 2002). Also *Networking* activities generate a base for the development of cohesion amongst actors (Johansson, 2006).

As is evident from this discussion, the influence of academic activities on the dynamics of the nanotechnological innovation system is not only direct in terms of commercialization that strengthens the process of 'entrepreneurial experimentation.' Instead, most of the impacts have an indirect effect on commercialization. For instance, 'resource mobilisation' in the form of educating skilled labour provides the required human capital to exploit various business opportunities and 'providing direct guidance' may help firms to choose the most promising application of their generic knowledge. Some of the effects are very uncertain though, and may occur after a long time lag. This may be particularly so for activities that impact on the process of 'legitimation' which, nevertheless, is a central process that determines access to markets and resources.

4. Explaining and improving the academic influence on the Swedish nanotechnological innovation system

The strength of the key processes in industrialisation is, of course, not only determined by activities pursued by academics but also by the other structural elements in the TIS as well as by factors that are exogenous to the system. The impact of academics on functional strength is, therefore, conditioned by the context in which they are situated. In particular, within the system and outside of it, there may be factors that constitute blocking mechanisms to the development of powerful functions. For instance, and as will be seen below, 'influence of the direction of search' is blocked by the persistent debate on risks with nanotechnology. The multitude of activities pursued by academics to strengthen that function is clearly counteracted by this factor. Moreover, functions are interdependent. For instance, a weak 'influence on the direction of search' will block 'entrepreneurial experimentation' as firms will search for opportunities elsewhere. Functional interdependencies may therefore magnify the effects of a given blocking mechanism.

In this section, we will analyse the context in which academics pursue their activities and explain the extent to which their activities actually strengthen system dynamics through their impact on the functions (4.1). A set of blocking mechanisms will be identified and these will form the base for a discussion of opportunities to improve the impact of academic R&D (4.2). For reasons of space, we will limit us to five of the functions, excluding market formation and development of positive externalities.

Figure 3 shows the impact of key blocking mechanisms on the functions and indicates policy opportunities to address these blocking mechanisms. In what follows, we will elaborate on this Figure.

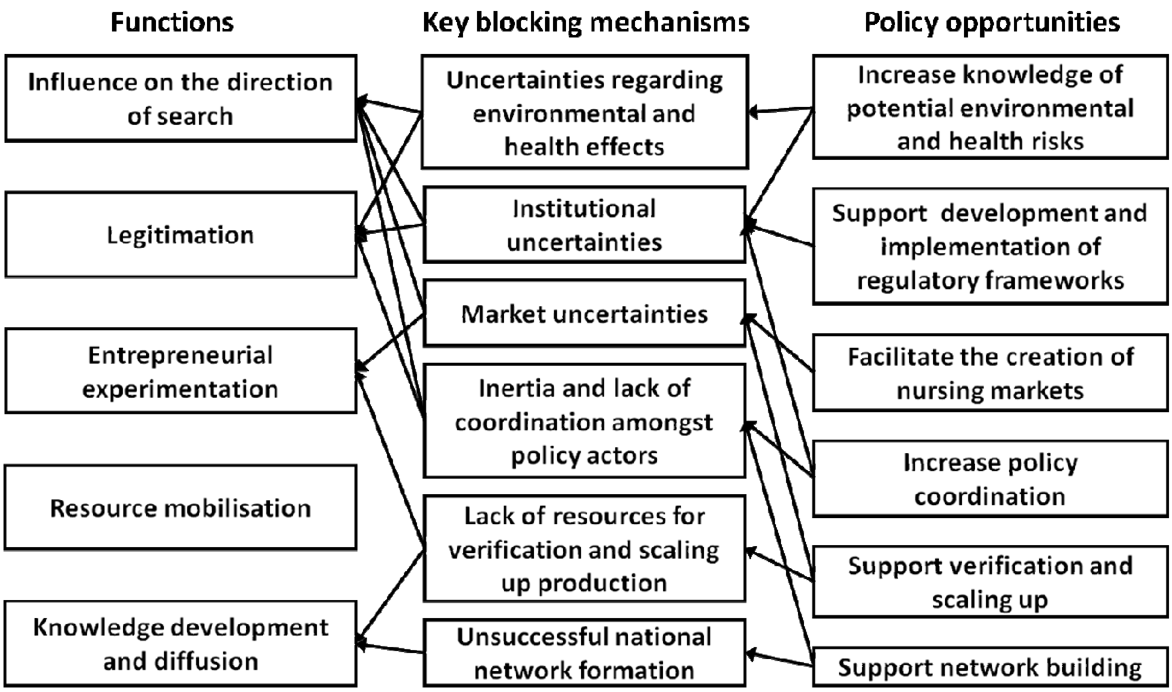

Figure 3 Key relations between functions, blocking mechanisms and policy opportunities

4.1 Explaining the influence

Influence on the direction of search is, as was shown above, impacted on by academia in many ways. Yet, it is a weak function.[11] Whilst there is a perceived large market potential, a strong international policy interest and a newly stirred national interest, established industry is not engaged in an extensive way (Fogelberg, 2008; Johansson, 2006; Perez and Sandgren, 2008). There are a large number of blocking mechanisms that explains the system weakness. Amongst the more prominent, we find uncertainties regarding a) environmental and health effects, b) institutions (e.g. regulations and beliefs) and c) markets. These uncertainties create scepticism and lack of commitment amongst established industry, countering academia's attempt of awakening an interest in the area (Kusoffsky, 2009; OECD, 2009; Perez and Sandgren, 2008).

The function is also weakened by lack of coordination amongst policy actors. Swedish governance of nanotechnology has been separated regarding research, innovation and risk handling, lacking a policy actor concerned with and capable of boosting nanotechnology related innovation processes (Fogelberg, 2008; Fogelberg and Sandén, 2008). In addition, the Swedish public research funding system demonstrates an inertia which obstructs the emergence of new technological areas, such as nanotechnology (Benner and Sandström, 2000). Indeed, academic activities targeted at influencing the funders of research receive a lukewarm interest (Fogelberg and Sandén, 2008).

As in the prior function, *Legitimation* combines much influence from academic R&D with a weakness of the process, formed by many blocking mechanisms. Though Swedish public acceptance of nanotechnology is relatively high (Scheufele et al., 2009; Wallerius, 2009), some companies are reluctant to being associated with the technology (Dahlöf and Wihed, 2010; Karhi, 2006; Kusoffsky, 2009). The reason for this is found in large uncertainties regarding environmental and health hazards

[11] The strength of the functions is estimated based on various data and informed actors' perceptions. Yet, as indicated above, there are large difficulties in measuring the strength of some of the functions.

(Dosch and Voorde, 2009; OECD, 2009). Additionally, the ability of the existing regulatory frameworks to support a sustainable development of the technology is perceived to be uncertain (Hassellöv et al., 2009; Kusoffsky, 2009; OECD, 2009). Initiatives taken by academia to rectify the situation have not been met favourably due to the above mentioned inertia and lack of coordination amongst policy actors.

Entrepreneurial experimentation is a fairly strong function and much influenced by academia in terms of both patenting and the formation of spin-off firms. Although existing firms are hesitant to diversify into nanotechnology (for reasons mentioned above), academic spinoffs continuously enter the system (Dahlöf and Wihed, 2010; Perez and Sandgren, 2008). Yet, market uncertainties obstruct the search for new applications, a central element of entrepreneurial experimentation (OECD, 2009). Lack of resources for verification and scaling up production also weakens the function (e.g. Andersson, 2009; Samuelson, 2009).

Resource mobilisation regarding human capital is much influenced by academia and is a strong function. Human capital supply is perceived as sufficient, and there is even a surplus (Malsch, 2008; Perez and Sandgren, 2008).

Knowledge development and diffusion is influenced by all academic activities but is only moderately strong. Sweden is perceived as a strong international actor in several sub-areas, although the bibliometric performance is not outstanding (Perez and Sandgren, 2008; Swedish Research Council, 2005). The knowledge base centres on scientific knowledge and is perceived as satisfying, even exceeding Swedish industry needs (Fogelberg, 2008). However, the lack of resources for verification and scaling up production hinders the development of market and production related knowledge (Perez and Sandgren, 2008). A lack of national social cohesion coupled to a lack of interest from some industrial actors, obstructs academia's efforts to form a national network; a prerequisite for diffusing knowledge (Perez and Sandgren, 2008).[12]

Summing up, *Influence on the direction of search* and *Legitimation* are central, although subtle and difficult to measure, functions in the emergence of the nanotechnology TIS. A broad range of activities by academic researchers have been geared towards these functions. Still, they remain weak, blocked by uncertainties regarding environmental and health effects, institutions and markets. Inertia among research funders and lack of coordination amongst policy actors constitute further blocking mechanisms. *Entrepreneurial experimentation* is a fairly strong function with a substantial, and measurable, impact from academia as is *Resource mobilisation* with respect to human capital. Academia has many activities which may impact on *Knowledge development and diffusion* and the function is quite strong but there are still significant blocking mechanisms.

As mentioned above, functions are interdependent and a mechanism blocking one function may, therefore, indirectly obstruct other functions. *Influence the direction of search* and *Legitimation* affect many other functions and are, therefore, of particular importance in the early development of a TIS (Bergek et al., 2008).[13] As revealed above, they weaken *Entrepreneurial experimentation* in that established firms, with some exceptions, are hesitant to diversify. A lack of funds for verification and scaling up (blocking entrepreneurial experimentation) may also be interpreted as a sign of poor *Legitimacy* in policy circles focusing on funding nanoscience rather than nanotechnology (Fogelberg, 2008). The mechanisms that obstruct *Entrepreneurial experimentation*, in turn, constrain the effects of academic activities geared towards *Resource mobilisation* and *Knowledge development and diffusion*. We noted a probable surplus of human capital and knowledge generated by academia, reflected by a lack of demand amongst industry.

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[12] Recently, networking has increased, partly due to incentives in the latest Swedish Research Bill (Swedish Research Council, 2009). Some knowledge diffusion exists in networks for specific issues, such as for building and using infrastructure, and for informal policy information sharing (Dahlöf and Wihed, 2009). There are also some strong local university-industry networks, built up during decades of cooperation.

[13] Yet, they are seldom emphasised in the science policy debate (Jacobsson and Perez Vico, 2010).

4.2 Improving the influence

The analysis reveals six mechanisms blocking the development of the TIS: uncertainties regarding environmental and health effects, institutions and markets; inertia and lack of coordination amongst policy; lack of resources for verification and scaling up production and underdeveloped national networks. These blocking mechanisms provide policy makers with guidance as regards opportunities for policy intervention. In what follows, we will discuss these opportunities but refrain from suggesting particular tools for policy intervention. The discussion will be centred on Figure 3.

First, policy may support *research on potential environmental and health risks* associated with nanotechnology. Providing research funding would enable both knowledge development and diffusion on different aspects of nanotechnology hazards (European Commission, 2009). It may also lead to a reduction of institutional uncertainties, since new knowledge may facilitate the alignment of institutions.

Second, policy may address such institutional uncertainties also by directly *supporting the development and implementation of regulatory frameworks*. Too rigid or too weak regulatory frameworks will decrease the value created by nanotechnology (Matsuura, 2006). Addressing the linkages between innovation and risk handling processes is essential and requires cooperation between regulators, developers and users (Matsuura, 2006).

Third, policy may facilitate *the creation of nursing markets*. The potential role of nanotechnology in addressing global issues, such as climate change, resource constraints and health has been highlighted (Dosch and Voorde, 2009; Manning, 2009). Incentives for using nanotechnology to meet these challenges may lead to the formation of nursing markets that could reduce market uncertainty.

Fourth, *policy coordination* needs to be increased. In a systems world, policy actors need to coordinate their interventions (Fogelberg, 2008). The presence of policy making bodies with a holistic competence and a leading policy actor with the required mandate and resources to lead such a process are necessary conditions for interventions to be coordinated. This would also facilitate resolving institutional uncertainties.

Fifth, policy may *support verification and scaling up* of production. Providing persistent support for these costly and time consuming processes would facilitate developing production knowledge and reduce market uncertainties. Finally, policy may induce the formation of national *networks* based on mutual interests of the actors (Fogelberg and Sandén, 2008; Perez and Sandgren, 2008).

5. Conclusions

The purpose of this paper was to analyse how academic R&D has influenced the commercialization of nanotechnology in Sweden and suggest how this influence can be enhanced by further policy intervention. We conceptualised this influence as the impact of a number of activities embedded within or sprung from academic R&D on a set of key processes in the growth of a technological innovation system centered on nanotechnology. Whilst some of the impact on commercialization was direct, in the sense of (many) academics setting up firms and applying for patents, we identified a whole range of indirect ways in which academia influenced commercialization. For instance, many activities are geared towards 'influencing the direction of search' of actors into the nanotechnological innovation system and to enhance the 'legitimation' of the new field. Academia also paved the way for commercialization through knowledge development and formation of human capital.

Yet, the impact of academia is constrained by a set of blocking mechanisms that obstruct the formation of strong functions. Six such mechanisms were identified and the impact of these may be magnified by the interdependencies of functions. Policy may enhance the academic impact by eliminating or reducing the strength of these blocking mechanisms. We addressed these opportunities for policy intervention suggesting, for example, that policy may support knowledge development on potential environmental and health risks, facilitate the formation of nursing markets and support verification and scaling up of production.

However, identifying and meeting these challenges, and others as the TIS evolves, requires a holistic policy competence and capacity to act strategically which Sweden is currently lacking. Unlike many industrialized countries, Sweden lacks a national nanotechnology strategy with dedicated funding. Such a strategy could constitute a platform to build this capacity but requires powerful measures and dedicated resources. A Swedish actor capable of building such a platform and with the capacity to mobilize the required resource and coordinate actions is currently missing. Forming such an actor is, perhaps, the largest policy challenge.

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