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REGULAR ARTICLE

Development blocks in innovation networks

The Swedish manufacturing industry, 1970–2007

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Abstract The notion of development blocks (Dahmén, 1950, 1991) suggests the co-evolution of technologies and industries through complementarities and the overcoming of imbalances. This study proposes and applies a methodology to analyse development blocks empirically. To assess the extent and character of innovational interdependencies between industries the study combines analysis of innovation biographies and statistical network analysis. This is made possible by using data from a newly constructed innovation output database for Sweden. The study finds ten communities of closely related industries in which innovation activity has been prompted by the emergence of technological imbalances or by the exploitation of new technological opportunities. The communities found in the Swedish network of innovation are shown to be stable over time and often characterized by strong user-supplier interdependencies. These findings serve to stress how historical imbalances and opportunities are key to understanding the dynamics of the long-run development of industries and new technologies.

Keywords Development blocks · Community detection · Network analysis · Technological imbalances

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1 Introduction

Innovation researchers and policy makers are well-aware nowadays of the fact that innovations do not appear in isolation. The ’systemic’ aspects of technology shifts have been stressed in a variety of empirical and theoretical accounts (Dahmén 1950; Rosenberg 1969; Gille 1978; Hughes 1987; Carlsson and Stankiewicz 1991; Nelson 1994; Bresnahan and Trajtenberg 1995; Helpman 1998; Freeman and Louça 2001; Perez 2002; Lipsey et al. 2005; Markard and Hoffmann 2016) and these perspectives permeate policy-oriented research based on the notions of national, regional and sectoral innovation systems (Lundvall 1992; Breschi and Malerba 1996; Malerba 2002; Cooke et al. 2004). The received literature proposes that technological change takes place by way of strong mutual interdependencies between certain industries, sometimes geographically localized, and that innovation activity is profoundly shaped by these interdependencies. Given these insights, the relevant empirical questions are: what industries and technologies are actually characterized by such interdependencies and how do such interdependencies evolve over time? The concept of *development blocks* gives an avenue for such a research agenda, emphasizing the dynamic interdependence of the components of large or small systems of technologies, from actor-networks to general-purpose technologies. In this view, strong incentives to develop new technologies are provided by the complementarities and imbalances that arise as development blocks evolve (Dahmén [1942], 1950, 1991; Carlsson and Stankiewicz 1991; Schön 1991, 2010). Delimiting the boundaries of development blocks and studying the complementarities and imbalances systematically is however typically a difficult affair. The present study addresses this problem, arguing that development blocks can be approached empirically by studying two facets of innovation activity: i) the flows of innovations across industries, ii) the problems and opportunities that spur innovation. This has been made possible by the construction of new literature-based database, SWINNO, containing over 4,000 Swedish innovation objects (Sjöö et al. 2014; Sjöö 2014; Taalbi 2014). Using this data, the aim of the present study is to describe interdependencies in the network of Swedish product innovations, 1970–2007. This description aims both to describe subsystems of innovations and to analyze the impulses to innovation that stem from imbalances and complementarities within development blocks. This is achieved by combining recently developed statistical techniques for community detection with analysis of biographic information on the problems and opportunities that have spurred innovations.

Three aspects of the network of innovations are studied:

– *Are there subsystems in the network of innovations?* The community structure of the network of innovations is explored to delineate closely interdependent industries.
– *What roles do industries have in innovation networks?* The structure of the network of innovations is explored statistically to describe the roles of industries as suppliers and users of innovation.

– *How have opportunities and imbalances provided incentives to innovations?* The qualitative character of innovation as response to problems and opportunities is explored through the lens of innovation biographies.

By answering these questions, the structure and character of technological interdependencies between industries can be described, arguably approaching Dahménian development blocks.

The outline of the paper is as follows. Section 2 discusses how industrial interdependencies are posited to affect innovation activity according to previous literature and discusses major differences between the notion of development blocks and related notions such as general-purpose technologies and technological systems. Section 3 introduces the literature-based innovation output database and the construction of the network of Swedish innovations. Section 4 explains the network and community detection analysis and presents the results from statistical analysis of the network of innovations and then discusses the qualitative character of problems and opportunities that have spurred innovations. Section 5 concludes.

2 Analyzing technological interdependencies

Historical studies tell us that innovations come about in bunches and as parts of broader technology shifts in which technologies *co-evolve*. The dynamics of broader technology shifts, arising by way of a series of co-evolving technologies, has been discussed in terms of general-purpose technologies (Bresnahan and Trajtenberg 1995; Helpman 1998; Lipsey et al. 2005), technological styles (Perez 1983; Tylecote 1994) or techno-economic paradigms (Freeman and Louça 2001; Perez 2002), technological systems (Hughes 1983; 1987; Carlsson and Stankiewicz 1991; Bergek et al. 2008) and development blocks (Dahmén 1950; 1991).

These concepts embody different levels of analysis and different views on the driving forces of innovation. One central difference between these perspectives is the varying emphasis put on positive and negative interrelations in the evolution of industries. In the theory of general-purpose technologies, interdependencies between supply industries and user industries emerge when user sectors improve and enhance the key input (Bresnahan and Trajtenberg 1995; Lipsey et al. 2005). Similarly, the notion of techno-economic paradigms stresses that “major innovations tend to be inductors of further innovations; they demand complementary ones upstream and downstream and facilitate similar ones, including competing alternatives” (Perez 2010, p. 188). Innovation may also be strongly induced by opportunities and demand generated in the activities of other firms or in user sectors. In numerous accounts (for instance Schmookler 1966; van Duijn 1983; Lundvall 1988; von Hippel 1988; DeBresson et al. 1996), innovations are considered demand-led, induced by customer-producer interactions and following patterns of demand for goods. In sum, existing interdependencies between firms, or sectors of economic activity, provide strong opportunities for innovation.

By contrast, other approaches have stressed the inertia present in technological development. Technologies evolve not only by the downstream improvement of new technologies, but by the solution of *imbalances* and techno-economic problems that appear throughout the life cycle of new technologies (Hughes 1983; Dahmén 1950; 1991; David 1990). The diffusion of new technologies simply takes time and requires the overcoming of numerous obstacles. These obstacles may be technical, economic, social or institutional in character. It has been claimed that this type of problem is one of the most important sources of innovation. For instance, Nathan Rosenberg (1969) noted that ”the history of technology is replete with examples of the beneficent effects of this sort of imbalance as an inducement for further innovation” (Rosenberg 1969, p. 10). A very similar view has been offered by Thomas Hughes' (1983, 1987) analysis of 'sociotechnical systems' that evolve through the emergence of 'salients' and 'reverse salients'. Reverse salients are backwards, underperforming components of the sociotechnical system that hamper the development of the sociotechnical system as a whole. The situation is resolved by the identification and resolution of 'critical problems', problems that hinder the technological expansion. In the view of Hughes, “[i]nnumerable (probably most) inventions and technological development result from efforts to correct reverse salient” (Hughes 1983, p. 80).

The notion of *development blocks* emphasizes the importance of both positive and negative interdependencies between industries or firms in the process of structural change. In its formulation by Dahmén ([1942], 1950, 1991), development blocks were understood as ”a sequence of complementarities which by way of a series of structural tensions, i.e., disequilibria, may result in a balanced situation” (Dahmén 1991, p. 138). The core mechanism in the evolution of development blocks is thus that obstacles and imbalances appear, which require the alignment of the technological frontier in other fields, or new innovations that solve technological problems, thus bringing forth sequences of complementarities that may stimulate further innovation. This core mechanism specified by Dahmén I will, for conceptual clarity, refer to as development blocks *sensu stricto*. Such interdependencies, however, also create broader complementarities between industries and firms, and the notion of development blocks is often discussed in broader terms as *complementary economic activities that are stimulated by innovations*.[1] The central dynamics of what I suggest to call a development block *sensu lato* is provided by the fact that innovations create complementarities between firms, technologies, industries or institutions and that new technologies or innovations in turn stimulate investment and development efforts in other firms or industries.

The notion of development blocks thus suggests, on a fundamental level, that interdependencies between parts of a system may be understood in both positive and negative terms. Positive interdependencies may arise due to increasing returns, positive externalities and path dependence in technology choices (Young 1928; Kaldor 1981; David 1985; Arthur 1989; 1990; 1994; David 2001). On the basis of positive externalities and increasing returns between agents of a system,

[1] Compare e.g. Carlsson and Stankiewicz (1991), Enflo et al. (2008) and Schön (2010), discussing the broader implications from the *sensu strictu* notion of development blocks. For instance, after giving a lucid exposition of Dahmén's notion *sensu strictu*, Carlsson and Stankiewicz (1991, p. 111) deal with the broader effects of the core mechanism in writing of development blocks as ”synergistic clusters of firms and technologies within an industry or a group of industries”.

structures of strongly interdependent agents, institutions and industries may emerge. On the other hand, precisely because of interdependencies, technological development typically requires the coming into place of other components. The lack of such components may become obstacles to further development and create *imbalances* that must be resolved.

Several previous studies have conducted empirical analysis inspired by the notion of development blocks (Schön 1990; Carlsson 1997; Enflo et al. 2008). Technological imbalances and complementarities between economic activities or technologies are however typically difficult to study empirically in a systematic manner. While development blocks may encompass a large variety of interdependencies in their effects, it is useful to separate the broader notion of development blocks from the core mechanism specified by Dahmén, which focuses on *innovations* as responding to imbalances and the opportunities that come forth through the diffusion of new technology. Focusing on this central dynamism, development blocks *sensu stricto*, the current study proposes a new method that approaches development blocks through the combination of textual evidence on innovations that respond to technological imbalances, and a quantitative approach to delineate related industries, using recent contributions to network analysis. As it were, it is possible to argue that the localization of development blocks can be done by addressing two aspects of the supply and use of innovations:

i the boundaries of industries that are closely related in terms of the supply and use of innovations,[2]

ii the character of innovation interdependencies as resulting from attempts to close technological imbalances.

It is thus submitted that development blocks can be approached by first assessing and describing the strength of innovational interdependencies between industries, and then assessing the character of these flows of innovations, as complementarities are supplied when innovations solve imbalances.

The first issue concerns the analysis and description of intersectoral interdependencies in terms of *subsystems*. Previous research has employed a wide set of approaches to analyze and describe economic, knowledge and technological interdependencies in terms of subsystems. The classical analysis of economic interdependencies has departed from Input-Output matrices of economic flows in which interdependencies could be analyzed as the ”dynamic inverse”, or in models of vertically integrated sectors (von Neumann 1945; Leontief 1941; Goodwin 1949; Pasinetti 1973; 1983). Sraffa (1960) and Leontief (1963) discussed the problem of finding subsystems in such economic flows. Leontief for instance proposed a block partition of non-zero elements in the Input-Output framework.

Similar in aim to the current study, Enflo et al. (2008) employed cointegration analysis between industrial production volumes in Sweden (1900–1970) to approach

[2]It is worth stressing that, as opposed to a more dynamic analysis that could lay claim to capturing broader complementarities in development blocks *sensu lato*, the claims of such an analysis must be modest, aiming only to *describe* the strength of innovational interdependencies between industries and delineate closely related industries.

development blocks. Studies in economic geography have measured industry relatedness by measuring the coproduction of different products on the plant-level (Neffke and Svensson Henning 2008; Neffke et al. 2011). Mappings of the patterns of production and use of inventions or innovations have been constructed since the 1980s (see Los and Verspagen 2002 for an overview), employing patent data (Scherer 1982; Verspagen 1997; van Meijl 1997; Nomaler and Verspagen 2008; Fontana et al. 2009; Nomaler et al. 2012), R & D flows (Leoncini et al. 1996; Leoncini and Montresor 2003; Montresor and Marzetti 2008) and innovation output data (DeBresson and Townsend 1978; Robson et al. 1988; DeBresson et al. 1996). The so-called technology flow matrices constructed with patent data have in general been used to measure the intersectoral spillover effects of knowledge. Robson et al. (1988) used a matrix of the number of innovations produced and used in industries, to draw conclusions about the location of innovative activity in Great Britain. These studies were for instance underlying Pavitt's 1984 seminal study and taxonomy of innovation. Recent research (Montresor and Marzetti 2008; McNerney et al. 2013; Garbellini and Wirkierman 2014) has suggested that subsystems in economic and R&D flows may be analyzed by way of network analysis and the detection of *communities*. This analysis can be extended to the case of innovation output flows. A *community* is then a set of industries that form close connections in terms of the flow of innovations.

Following these lines of inquiry, the current study describes and analyzes the overall interdependencies and flows of innovations between industries by mapping the number of innovations in a product group to the respective sectors of use. The resulting "Object Matrix" (Archibugi and Simonetti 1998) informs us of in what sectors innovations were produced and used, and may be considered a measure of the linkages between product groups and sectors of economic activity. The raw statistics of the innovation flow matrix can be used to describe what sectors were salient sectors of supply and use of innovations, and how these patterns have changed during the period 1970–2007. An analysis of related industries can be carried out in a statistical approach using network analysis and community detection, which describes those industries that are closely related in terms of the supply and use of innovations.

The second issue to be addressed is to what extent innovation activity takes place by way of the exploitation of technological opportunities and downstream improvement of key inputs or rather by way of overcoming hurdles. There is a somewhat extensive literature of innovation or industry case studies (see e.g. Rosenberg 1969; Hughes 1983; Dedehayir and Mäkinen 2008; 2011). However, this issue has been much less studied systematically and in relation to statistical macro-evidence of technological interdependencies. Fortunately, the SWINNO database also gives a rare opportunity to study jointly these two central facets of technology shifts: the response to technological imbalances, and innovation as the response to and downstream improvement of technological opportunities.

In sum, Dahmén's concept of development blocks can be understood as sets of complementarities that appear sequentially as economic agents solve technological imbalances. Combining statistical and qualitative analysis the communities of closely related industries may be said to reflect *development blocks* if innovations create complementarities within the communities, or if innovations are "gap filling", i.e. respond to technological imbalances by supplying missing components or factors in a relation of complementarity. Thus, communities indicate development blocks *if* the qualitative character of interdependencies can be assessed as supplying complementarities by solving imbalances.

3 Data

SWINNO (Swedish innovations) is a recently constructed longitudinal micro-database containing extensive information about over 4,000 single product innovations commercialized by Swedish firms between 1970 and 2007 (Sjöö et al. 2014).[3] Previous databases capturing inter-sectoral flows of innovations have been either patent based (Scherer 1982; Verspagen 1997; van Meijl 1997; Nomaler and Verspagen 2008; Nomaler et al. 2012) or innovation output based, employing expert opinions as sources of data (Townsend et al. 1981; Pavitt et al. 1987). The underlying approach of the SWINNO database is the literature-based innovation output method (LBIO) (Kleinknecht and Bain 1993). The database was constructed by scanning 15 Swedish trade journals, covering the manufacturing industry and business services, for independently edited articles on product innovations. Apart from ensuring a coverage of all major ISIC 2-digit manufacturing industries, these trade journals were selected with the criterion that journals are not affiliated with any company or otherwise biased and that the journal has an editorial mission to report on technological development of the industry. The edited sections of journals were in turn scanned for innovations, defined in SWINNO as *an entirely new or significantly improved good, process or service that is transacted on a market*. Moreover, only innovations developed by Swedish companies are covered, in part because the editorial mission of the trade journals is more or less confined to the Swedish market.[4]

Table 1 describes the basic information used in this study. The available information has enabled the construction of data about product types (ISIC codes), user industries (ISIC codes) as well as the factors that have spurred innovation activity. All these variables are possible to study over the period 1970-2007 since the year of commercialization is recorded for all marketed innovations.

The innovation biographies have made possible a classification of the factors that have spurred innovations in two main classes: opportunities and problems. The classification into problem-solving and opportunity driven innovations has departed exclusively from information available in the more than 6,000 trade journal articles and was carried out by scanning the journal articles manually (i.e. without aid from text analysis software) by the present author. Classifications were made in keeping with two principal considerations. First, an innovation was considered problem-solving if the development of the innovation was explicitly described as driven by an aim to overcome an obstacle or problem, which may be of an economic, social or technological character. Importantly, our concern is only with those problems that the

[3] An extension of the database to 2014 was finished in May 2016.

[4] For further details on methods and selection procedures, see Sjöö et al. (2014).

Table 1 Description of key variables from the SWINNO database

Variable	Description
Commercialization year	Year of commercialization of the innovation according to journal article.
Product type	The product code (ISIC Rev 2) of the innovation.
User sector	The sector in which the innovation is or is going to be used according to the journal article. User sector specified as industries (ISIC Rev 2), final consumers or general purpose.
Problem solving	The articles cite a problem as an impulse or motivating factor for the development of the innovation.
Opportunities	The articles cite a new technology or scientific advance as enabling the innovation.

innovation was developed to solve. While there are typically some technical problems or obstacles to overcome *in the course* of the innovation process, these are not of concern to the present analysis. In practice, an operational definition of a problem lies close to the notion of obstacle, i.e. a factor that impedes the attainment of some firm-specific, industrial or societal goal. In other cases the description of the innovation process allowed for the distinction of a factor that the firm managers *perceived* as a problem that needed to be solved. Thus, an innovation was considered problem-solving if the development of the innovation was explicitly described as aiming to overcome an obstacle or problem as defined previously. For each problem-solving innovation a note was taken of this textual evidence, which has served as the basis of qualitative descriptions found in Section 4.5.

Second, an innovation was considered to exploit technological opportunities if the journal articles explicitly mentioned a technology or scientific advance that had enabled or contributed to the development of the innovation.[5]

3.1 Data coverage

This study covers product innovations launched in the Swedish manufacturing industry and business services (including software, supply of telecommunication network services and technical consultancy).[6] A product innovation is in the SWINNO database defined as any innovation that is being traded on a market, in contradistinction with process innovations, defined as innovations being withheld from markets and applied in-house only (Sjöö et al. 2014).

[5]While the definitions of problems and opportunities are conceptually distinct *per se*, it does occur that innovations find driving forces both in opportunities and problems. For instance, a new technology could make it possible to develop an innovation that solves a long standing problem for an industry. In such a case the innovation has been classified as being both opportunity driven and problem solving.

[6]The exclusive focus on innovations developed by Swedish agents should make it clear that the study ignores the supply of innovations developed abroad. While the patterns discovered in the ensuing analysis are certainly indirectly affected by the international problems, opportunities and advances in technology, the study should be understood as an analysis of ’domestic’ patterns of innovation.

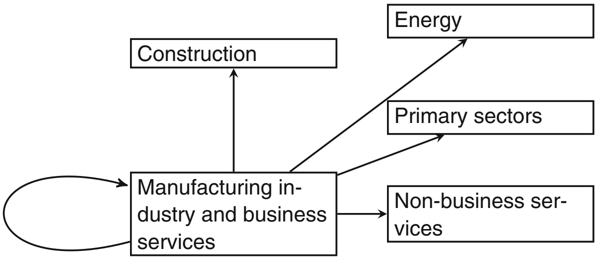


Fig. 1 The flows studied

Figure 1 illustrates the inter-sectoral flows of product innovations that are studied. While only innovations stemming from manufacturing and business services are studied, these innovations can be used across the board. Conversely, since the scope of the database is manufacturing and business services, innovations stemming from the primary sectors, construction, energy and non-business service are not captured other than on occasion when manufacturing journals report on innovations from outside of their primary scope. Thus, these sectors are always potential users of innovation, but agricultural, forestry, mining, construction, energy or non-business service innovations are only recorded occasionally. These cases have been retained in the current study (compare Table 2).

3.2 The construction of the innovation flow matrix

In order to analyze the innovation networks across industries, categorizations of the supply and user industries were constructed based on the information available from trade journal articles. The product innovations found in the journal articles were categorized in the Swedish Industrial Classification system 2002 (SNI 2002) corresponding to ISIC Rev 2 (henceforth referred to as ISIC). The variable "User" describes the sectors in which the innovation is used or explicitly intended to be used according to the trade journal articles. This refers strictly to the commercial use of the innovation, ruling out knowledge spillovers, but no other restrictions on the variable are imposed. The user sector may also refer to the use of innovations within the innovating firm (in which case it is recorded by the sector of the firm). Clearly, any innovation may have several user sectors, the maximum number of user sectors observed in practice being eight. The user sectors were classified at the lowest industry-level possible. The level of classification thus may vary. Whereas most user sectors are specified on a three or four digit ISIC level, some innovations are directed towards broader sectors corresponding better to two digit ISIC levels.

Apart from the given user industries two auxiliary user categories have been registered: final consumers and general purpose. The former category refers to innovations for private use. The latter category refers to innovations that were of a general-purpose character, i.e. described as used or possible to be used in any sector of economic activity. As the auxiliary categories of final consumption and general

Table 2 Aggregated Innovation Flow Matrix, Total economy, 1970–2007

Sector (ISIC)	Agri. & forestry (A)	Fishing (B)	Mining (C)	Manuf. (D) .	Electricity (E)	Construction (F)	Whole sale & retail (G)	Hotels & rest. (H)	Transport & communic. (I)	Financial (J)	Real est., & business act. (K)	Public adm. & def. (L)	Education (M)	Health & soc. sec. (N)	Other services. (O)	Final consumption	General purpose	Total supply
Agri. & forestry (A)	1.5	0	0.33	0.66	0	0	0	0.5	0	0	0	0	0	0	0	0	0	3
Mining (C)	1.5	0	0	2	0	0	0	0	0	0	0	0	0	0	0.5	1	0	5
Foodstuff, bev. & tobac. (DA)	1	0	0	13	0	0	1.5	8.83	1	0	0.33	0	0	0	0	43.33	1	70
Textiles (DB-DC)	1.5	1	0	9	0	2	0	0	0	0	0.5	2	0	1	2	5	3	27
Wood (DD)	1	0	0	13	1	33	0	0	1.5	0	0	0	0	0	1	6.5	8	65
Pulp & paper (DE)	1	0	0	33.99	1	5	1.5	0	3	0	0	0	0	0	0	4.5	12	62
Coke, ref. petrol. & nucl. fuel (DF)	0	0	0	1	3	2	0	0	0	0	0	0	0	0	0	1	1	8
Chemicals (DG)	8	0	2	56.51	0.5	9.7	1	0	2	0	3	0	0	39.75	7.5	11.03	16	157
Rubber & plastic (DH)	4.5	1	2.83	90.66	3	22.33	3.08	0	14.17	0	1.25	7	0	3	2	14.17	19	188
Other non-metallic mineral prod. (DI)	0	0	0	12	0	17.25	0	0	0.25	0	0	1	0	0	0	1.5	3	35
Basic metals & fabr. metal prod. (DJ)	2.5	1	10.73	162.21	7.5	44.49	0.33	2	17.2	1	0.7	4.5	0	3	1.5	20.33	38	317

Table 2 (continued)

Sector (ISIC)	Agri. & forestry	Fishing	Mining	Manuf.	Electricity	Construction	Who l e sale & retail	Hotels & rest.	Transport & com- munic.	Financial	Real est., & busi- ness act.	Public adm. & def.	Education	Health & soc. sec.	Other ser- vices.	Final con- sump- tion	General purpose	Total supply
	(A)	(B)	(C)	(D) .	(E)	(F)	(G)	(H)	(I)	(J)	(K)	(L)	(M)	(N)	(O)			
Machinery & eq (DK)	61	2	35.4	527.9	19.58	59.03	14.43	3.25	51	1	9.85	21.7	1.83	9.33	3 1.28	57.42	248	1154
Electrical & optical eq. (DL)	6.93	1	13.96	358.25	33.53	23.81	12.82	2.68	72.85	5.45	71.23	29 .87	2	88.13	12	132.5	407	1274
Transport eq. (DM)	4.17	1	4.5	83.71	1	5.33	1.33	0	56.2	0	3.33	26.33	0	2	5.33	15.75	19	2 29
Manuf. n.e.c. (DN)	0.5	0	0	10.5	0	2	0	0	0	0	0	1	0	0	0.5	8.5	17	40
Electricity (E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Construction (F)	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	1	7
Wholesale & retail (G)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2
Transp. & communic. (I)	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	4	7	14
Financial (J)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Real est. & business act. (K)	4	0	5.7	119.04	6.5	13.5	4	0	11.17	3	29.92	5	2	9	11.33	22.83	90	337
Health & soc. sec. (N)	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	2
Total use	99.1	7	75.46	1493.48	76.62	245.45	40	17.26	233.33	10 .45	120.11	98.4	5.83	156.21	74.95	353.37	891	3998

Note: Rows are supplying sectors, columns are user sectors.

purpose do not indicate specific linkages between industries they are not included in the analysis of communities.[7]

The innovation flow matrix (IFM) is an analytical tool that allows one to picture and analyze the supply and use of innovations and the linkages between industries. It is constructed by mapping the innovations developed in industry i that are used in sector j, for final consumption, or for general purposes. Using matrix notation, the innovation flow matrix can be expressed as a $N \times N$ matrix $\mathbf{W}$, expressing intersectoral supply and use of innovations. For a full representation of the supply and use of innovations, one may also include $1 \times N$ vectors $\mathbf{FC}$ and $\mathbf{GP}$, expressing innovations for final consumption and general purpose, respectively. In extensive form:

$$(\mathbf{W}, \mathbf{FC}, \mathbf{GP}) = \begin{pmatrix} W_{11} & W_{12} & \dots & W_{1N} & FC_1 & GP_1 \\ W_{21} & W_{22} & \dots & W_{2N} & FC_2 & GP_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ W_{N1} & W_{N2} & \dots & W_{NN} & FC_N & GP_N \end{pmatrix} \quad (1)$$

In theory, the flow matrix can be constructed by counting the number of innovations of type i that are directed towards user sector j. We then obtain a matrix, mapping the number of times an innovation in the database is found to be of product group i and used in sector j.

However, in practice we observe that an innovation may have several user sectors. Depending on the purpose of analysis, one may either count all observed linkages between sectors or count each innovation only once by applying a weighting procedure. In the first case an innovation with two user sectors is counted as two observations. This method gives a relatively large weight to innovations that are used in many different sectors. The first method may be preferred if the study aims to analyze the economic impact or diffusion of innovations in the economy.

By contrast, the second method implies that the more user sectors an innovation has, the *weaker* the linkage between two specific sectors of supply and use. If an innovation has two different user sectors, each of these linkages is given a weight of 1/2, ascertaining a total sum of 1. The second method is suitable for studying the strength of technological linkages between certain sectors, which is the purpose of the analysis in this study.[8]

This study follows the second method. Thus, each linkage between a supply and a user sector has been weighted by the inverse of the innovation's total number of observed user sectors. The second innovation flow matrix W is constructed by taking the sum of all weighted linkages between industry i and industry j. The elements W_{ij} of the matrix are thus weighted sums and will not be integers. However, since each

[7] Including these categories in a formal analysis would moreover exaggerate the linkages between industries since two product categories, for instance mobile telephones and foodstuff innovations, can be developed for final consumers, while having no direct industrial links.

[8] Though not essential for the current analysis, the second method is also consistent with a probabilistic treatment of the flow of innovations, since the calculation of the probability that an innovation is used in a certain sector is straightforward. This e.g. makes possible the analysis of the IFM matrix as a stochastic Markov process where the matrix $W_{ij}/\sum_j(W_{ij})$ is the transition matrix. Compare, e.g., DeBresson and Hu (1996).

innovation is only counted once, the row sums W_i will be equal to the count of innovations supplied. Formally, given a set of N innovations indexed by $k \in \{1, 2, ..., N\}$, each innovation has a number of observed user industries, denoted U. The weight w for a linkage of innovation k is then $w_k = (1/U_k)$. Assigning each weight to its respective supply and user industry, i and j respectively, we obtain the innovation flow matrix W with elements $W_{ij} = \sum_k (w_{ijk})$. In what follows, all statistics on the supply and use of innovations refer to weighted sums calculated according to this method.

The treatment of general-purpose innovations is an exception from the weighting procedure that merits further explanation. General-purpose innovations could in principle be counted by giving a (small) weight to each user industry (e.g. signifying a small probability that the innovation would be used in a certain industry). However, as general-purpose innovations do not inform of particular relations among industries, they have been retained as a separate category and are not part of the inter-industry flows. Innovations that are recorded as general-purpose innovations are thus counted separately and do not enter the weighting procedure.

4 The structure of the Swedish innovation network

This study is concerned with three aspects of the network of innovations:

– The community structure of the network.
– The supply and use structure of the network of innovations, i.e. the structural position of industries as suppliers or users of innovations.
– The character of innovational interactions, i.e. if innovations within development blocks are driven by techno-economic problems or exploiting new technological opportunities.

4.1 Supply and use of innovations

Table 2 presents the supply and use of innovations at the aggregated level for the period 1970–2007. Clearly, most innovations were aimed for use in other production and service activities. Innovations for use in manufacturing corresponded in total to roughly a third of the total count, throughout the period (36.5% in 1970–1989, 38.5% in 1990–2007). Innovations for use in services (ISIC G-O) corresponded in total to 18.9% during the period. General-purpose innovations accounted for 22.3% of the total count of innovations. Electricity, gas and water supply (ISIC E) and construction (ISIC F) corresponded to small shares (1.9% and 6.1% respectively). Table 2 also shows that for most of the supply industries the majority of innovations was used in other manufacturing industries. Exceptions were wood and wood products (ISIC DD) and other metallic mineral products (ISIC DI) that found use in construction, and chemicals and chemical products (ISIC DG) that to a very large extent found use in health care (ISIC N).

Figure 2 shows the count of innovations by user destination and year of commercialization over the period studied. The changes in the composition of user sectors reflect a structural shift from traditional sectors towards ICT. In the beginning of the

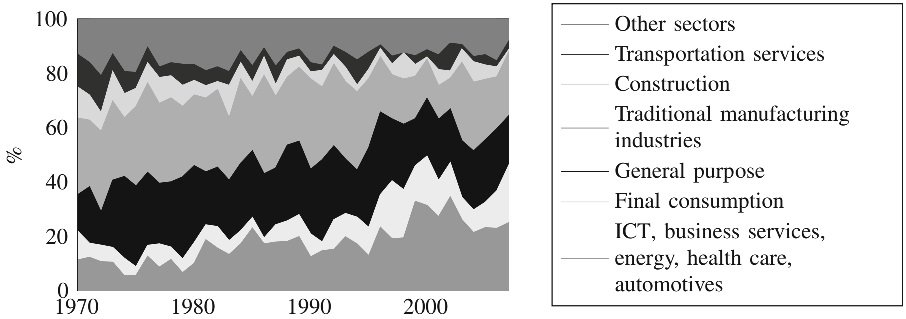


Fig. 2 Innovations by user industries, final consumption and general purpose, 1970-2007. Share of innovations in total annual count (%)

period, a large share of the innovations was to be used in the traditional manufacturing sectors, including foodstuff, pulp and paper, chemical, basic metals and the engineering industries. The share of traditional industries was 28.2% in 1970, decreasing to 14.4% in 2000. In the 1990s, focus instead shifted towards the ICT industries, business services, energy production, health care and the automotive industry. In particular, ICT increased from 11.3% in 1970 to 31.4% in 2000. The number of general-purpose innovations was rather constant throughout the period. Almost half of the innovations for general purposes (407 out of 891) were electronic equipment innovations (ISIC DL). Innovations for final consumption did not constitute a large share of the total count (8.8%) but increased during the 1990s, concomitant with an increase in the supply of telecommunication equipment innovations and final customer oriented software innovations.

In Table 3, stronger linkages between manufacturing industries are highlighted (above 10 innovations are highlighted in light grey, above 50 are highlighted in dark grey). The table allows a broad comparison between the main types of innovation, basic metals and fabricated metal products (ISIC DJ), machinery (ISIC DK) and hardware ICT products (ISIC DL). The main user industries of ICT products were health care (ISIC N), other business activities (ISIC K) and industries within the hardware ICT sector (ISIC DL).

By contrast, the principal user industries of machinery innovations were traditional manufacturing industries, e.g. the pulp, paper and printing industries (ISIC DE), fabricated metal products and basic metals (ISIC DJ), foodstuff (ISIC DA), and the construction (ISIC F) and agriculture and forestry sectors (ISIC A). User industries of basic metals and fabricated metal innovations were construction (ISIC F) and transport equipment (ISIC DM). A large portion was aimed for internal use or other parts of the metals sector.

4.2 Network analysis of intersectoral patterns of innovation

In Table 2, the innovation flow matrix has been presented at a fairly aggregated level. The full detail innovation flow matrix however is a 98 × 98 matrix, with 9,604 possible entries (excluding innovations for final consumption or general purpose). A

Table 3 Innovation flow matrix of innovations used in manufacturing industries, 1970–2007

Sector (ISIC)	Foodstuff, bev. & tobac. (DA)	Textiles (DB-DC)	Wood (DD)	Pulp & paper (DE)	Coke, ref. petrol. &nucl. fuel (DF)	Chemicals (DG)	Rubber & plastic (DH)	Other non-metallic mineral prod. (DI)	Basic metals & fabr. metal prod. (DJ)	Machinery & eq. (DK)	Electrical & optical eq. (DL)	Transport eq. (DM)	Manuf. n.e.c. (DN)	Total supply 15-37	Total supply
Agri. & forestry (A)	0	0.33	0	0.33	0	0	0	0	0	0	0	0	0	0.66	3
Mining (C)	0	0	0	0	0	0	0	0	2	0	0	0	0	2	5
Foodstuff, bev. & tobac. (DA)	10	0	1	0	0	1	0	0	0.5	0.5	0	0	0	13	70
Textiles (DB-DC)	0	3	0	2.5	0	1.5	0.5	0	0	0.5	0	0	1	9	27
Wood (DD)	0.5	1	6.5	0	0	0	0.33	0	0	0	0	0	4.67	13	65
Pulp & paper (DE)	9.5	0	3.33	14.33	0	1	1.83	0	1.17	1.33	0	1.5	0	33.99	62
Coke, ref. petrol. & nucl. fuel (DF)	0	0	0	0	0	0	1	0	0	0	0	0	0	1	8
Chemicals (DG)	3	3.25	4	9.83	0	7	6.33	0	5.33	1.12	8.05	5.57	3.03	56.51	157
Rubber & plastic (DH)	36.08	0.83	4	2.75	0	4.08	5.17	3.33	3.14	11.23	1.93	16.29	1.83	90.66	188
Other non-metallic mineral prod. (DI)	0	0	0	0	0	0.5	0.5	2	3.75	1.75	0	3.5	0	12	35
Basic metals & fabr. metal prod. (DJ)	9	1.5	11.08	2.75	0	2	4	1	51.1	28.77	12.88	32.54	5.59	162.21	317

Table 3 (continued)

Sector (ISIC)	Foodstuff, bev. & tobac. (DA)	Textiles (DB-DC)	Wood (DD)	Pulp & paper (DE)	Coke, ref. petrol. & nucl. fuel (DF)	Chemicals (DG)	Rubber & plastic (DH)	Other non-metallic mineral prod. (DI)	Basic metals & fabr. metal prod. (DJ)	Machinery & eq. (DK)	Electrical & optical eq. (DL)	Transport eq. (DM)	Manuf. n.e.c. (DN)	Total supply 15-37	Total supply
Machinery & eq. (DK)	63.32	29.17	49.3	104.09	1.92	35.77	21.72	3.26	89.44	38.77	19.83	60.11	11.2	527.9	1154
Electrical & optical eq. (DL)	22.09	1.83	25.57	63.34	4.64	28.12	6.1	1.55	49.39	20.47	84.74	50.41	0	358.25	1274
Transport eq. (DM)	0.7	0	1.83	0.58	0.25	0.2	0.5	0	1	3.67	0.4	74.58	0	83.71	229
Manuf n.e.c. (DN)	0	0	0	3	0	0	0	0	5.5	1	0	1	0	10.5	40
Electricity (E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Construction (F)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
Wholesale & retail (G)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Transport & communic. (I)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
Financial (J)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Real est. & business act. (K)	3.5	1	4	34.53	0	9.83	8.53	1.2	13.74	11.43	14.45	13.33	3.5	119.04	337
Health & soc. sec. (N)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Total use	157.69	41.92	110.62	238.05	6.8	91	56.52	12.35	226.07	120.52	142.28	258.83	30.83	1493.48	3998

Note: Rows are supplying sectors, columns are user sectors detailed description of the flow of innovations and the presence of subsystems in the IFM requires the use of more sophisticated descriptive statistics due to the complexity and size of the data. The preferred vehicle of analysis is network analysis and community detection analysis.

A network, or a graph, consists of relations, called edges (e.g. innovations), between entities, called vertices (e.g. industries). Formally, a graph is defined as $\Gamma = (V, E)$, where V is a set of vertices and E is a set of edges $E \subset V \times V$. The innovation flow matrix can be understood as a directed weighted network with the sectors as vertices (industries) and with the weighted number of innovations between industry i and industry j as edges. This means that both the count of innovations and the direction of the connections between industries matter. For a directed weighted network, each edge from vertex $i \in V$ to another vertex $j \in V$, has a weight $W_{ij} \in \mathbb{R}^{+}$.

Graphs may to a greater or lesser extent be possible to subdivide into subgroups, called communities. In a graph, in which all nodes are connected there is a weak community structure. In a graph in which some nodes are connected but not to all other nodes, there is a stronger community structure. The development of network theory has made it possible to find subgroups within a system of economic or technology flows. See Fortunato (2010) and Malliaros and Vazirgiannis (2013), for reviews of community detection approaches in undirected and directed networks.

There is a plethora of approaches to divide networks into subgroups, each with merits and limitations.[9] The most common approach, by far according to Fortunato (2010), is based on the concept of modularity (Newman 2004), which is a descriptive statistic (or quality function) designed to measure the strength of a division of a network into communities. The modularity approach is well-suited to our analytical purposes and data. The approach is based on maximizing the modularity statistic, which can be intuitively interpreted in the current research context as the share of innovations that flow within given communities less the expected share of innovations (see Eqs. 2a–2b). The maximum modularity partition thus gives the set of communities that have *most innovations above expected within communities and the least between communities*. Second, the modularity approach can be straightforwardly and directly applied to directed weighted networks (such as the IFM) without prior transformation (e.g. dichotomization and re-scaling), thus exploiting the richness of the data to a full extent.[10]

[9] Modularity-based methods, spectral algorithms, dynamic algorithms and statistical inference based methods, such as Bayesian inference methods and blockmodeling, are some examples. Subsystems in economic and technology networks have been studied through, e.g., modularity-based approaches (McNerney et al. 2013; Garbellini and Wirkierman 2014), statistical inference based methods (Leoncini et al. 1996; Montresor and Marzetti 2008; Piccardi 2011) and the so-called qualitative input-output analysis (Schnabl 1995). See Garbellini (2012) for an overview of methods applicable to economic input-output data.

[10] Other than ease of interpretation and application to our data, a useful property is that the modularity statistic can compare the quality of the results produced by different algorithms, which is desirable as there exists no *a priori* best-practice algorithm. Other desirable properties of this approach include that the number of communities is adapted by the algorithm rather than decided beforehand. One of the well-known limitations of community detection algorithms is however the presence of a resolution limit that may prevent the algorithm from detecting relatively small communities as compared with the graph as a whole (Fortunato and Barthélemy 2007). Specifically, Fortunato and Barthélemy (2007) found that communities

The modularity Q of a network is defined as the sum of share of edges that fall into communities minus the expected shares of such edges:

$$Q = \text{(share of edges within communities)} \\ -\text{(expected share of edges within communities)} \quad (2a)$$

Formally, in our directed innovation network W_{ij}, the modularity is calculated as

$$Q^{dir} = \sum_{ij} \left(\frac{W_{ij}}{k} - \frac{k_i^{out} k_j^{in}}{k^2} \right) \delta_{c_i c_j} \quad (2b)$$

where $\frac{W_{ij}}{k}$ is the actual shares of flows between industry i and j, and k is the sum total of flows in the network. The expected shares of flows from industry i to j is calculated as the product of the share of innovations supplied by i, k_i^{out}/k, and the share of innovations used by j, k_j^{in}/k. The expected share of innovations assuming a random distribution is $\frac{k_i^{out} k_j^{in}}{k^2}$. $\delta_{c_i c_j}$ (the so-called Kronecker delta) assumes values 1 if $c_i = c_j$ i.e. if i and j belong to the same community, and 0 otherwise. A particular advantage with this formulation is that the modularity approach thus adjusts for the scale of industries since the expected share of innovations is based on the total number of innovations supplied and used.

The value of modularity lies between -1 and 1, being positive if the number of edges or weights within groups exceeds the number of edges or weights expected. Modularity approaches 1 when no edges flow between communities and all edges flow within communities. Conversely, modularity approaches -1 when no edges flow within communities but only between communities. According to Clauset (2004, p. 2) "in practice it is found that a value above about 0.3 is a good indicator of significant community structure in a network."

The problem of finding a community division that maximizes modularity is NP complete (Brandes et al. 2006) and non-trivial. While attaining the same end-goal, there are several algorithms proposed to solve the problem, each with merits and limitations. Since there is no algorithm that finds the community division that maximizes modularity *a priori*, the results section compares three similar community detection algorithms that are suitable for weighted networks. Newman (2004) proposed an efficient "greedy search" algorithm, in which vertices are joined into the same groups if they achieve the largest increase in modularity. Here the improved algorithm by Clauset et al. (2004) is used. The algorithm proposed by (Clauset et al. 2004) is

containing fewer than $\sqrt{k}$ edges may in fact contain smaller communities, even in a maximum modularity partition, where k is the number of edges in the graph. Because of this, the results should be interpreted with care as there may exist further subgroups within the communities found. An arguable limitation of the current approach is also that communities are *partitions*, i.e. mutually excluding. Possible extensions of the current approach would therefore be to allow communities to be overlapping, meaning that a sector is allowed to belong to more than one community. Algorithms overlapping community detection are currently a major focus for research, but there are currently only a few available modularity-based algorithms (e.g. Nicosia et al. 2009; Wang et al. 2013) and no metric for deciding whether to use disjoint or overlapping communities.

efficient and widely used but limited to undirected weighted networks. Thus, the total count of innovations flowing between two industries is taken into account, but not the direction of the flows.

A spectral bisection algorithm for detection of community structures in weighted *directed* networks was suggested by Leicht and Newman (2008), generalizing the suggestions of Newman (2006) to directed networks. The task of the algorithm is to yield a subset of vertices that maximize the modularity, by way of a process of repeated bisection (i.e. subdivision into two partitions). The algorithm arrives at communities that are further indivisible, i.e. any further division into new communities does not improve modularity.

The first algorithm was applied using the igraph package (see Csardi and Nepusz 2006) in software environment R. The two latter algorithms for weighted undirected and directed graphs were executed by the author in software environment R, following Leicht and Newman (2008) and the fine tuning algorithm described in Newman (2006).

During the period studied there are stable patterns in the supply and use of innovations. The results are summarized in Tables 4 and 5. The results first of all indicate the existence of a strong community structure. With all three methods, the network partitions result in a modularity above 0.3, which indicates a significant community structure. The highest modularity is yielded by the fast greedy algorithm (Clauset et al. 2004), suggesting ten communities in the innovation flow matrix for the period 1970–2007. The other two algorithms suggest ten and eleven communities but have slightly lower modularity. The importance of the proposed community structure is assessed by the modularity statistic. The modularity of the community is 0.34 for the whole period. The innovations flowing within the communities capture 45% of the total count of innovations. Moreover, the results from the three different community detection algorithms are similar. An indication of the robustness of the partitions may be obtained by calculating the NMI (Normalized Mutual Information), which compares the similarity between the proposed partitions (Danon et al. 2005). The similarity between partitions is reported in Table 4. The statistic ranges between 0, if the partitions are disjunct, and 1, if the partitions are identical. The lowest found

Table 4 Summary statistics of partitions for IFM 1970–2007

	Fast greedy	Leading eigenvector (undirected)	Leading eigenvector (directed)
Modularity	0.3430	0.3067	0.3424
N. communities	10	10	11
NMI			
Fast greedy	1	0.6440	0.7672
Leading eigenvector (undirected)	0.6440	1	0.6713
Leading eigenvector (directed)	0.7672	0.6713	1

Normalized mutual information (NMI) compares the similarity between the partitions of networks into communities.

Table 5 Description and summary statistics of communities suggested by the fast greedy algorithm for IFM 1970–2007

Brief description of community	Sum of weights within	Count of innovations involved[a]	Count of innovations involved including GP and FC[b]
1. Pulp and paper	134.82	187	324
2. Food products and packaging	129.81	151	303
3. ICT innovations	219.04	268	715
4. Automotive vehicles and land transportation	155.56	202	329
5. Medical	120.11	128	135
6. Forestry	47.67	50	55
7. Construction, metals and wood	404.88	451	642
8. Shipbuilding, aircraft and military defense	50.34	57	69
9. Electricity	48.61	82	172
10. Textiles and clothing	30.69	34	44
SUM	1341.51	1610	2788
Total IFM[c]	2743.63	3998	3998

[a]Count of innovations for which there is at least one linkage within the respective communities.

[b]Total count of innovations for which there is at least one linkage within the respective communities, including innovations for general purpose or final consumption.

[c]In the first row, the total refers to the total sum of weights in the IFM 1970–2007, when innovations for general purpose or final consumption are excluded. In the second and third column these are included for comparison with the count of innovations involved in communities.

NMI is 0.6440, whereas the NMI between the partition suggested by the fast greedy and leading eigenvector algorithm for directed networks is 0.7672.[11]

While the results are similar, the fast greedy algorithm finds the best partition.[12] The communities suggested are described in Table 5, where they have been labelled according to the most significant sector of supply or use.

[11]Following Danon et al. (2005) the normalized mutual information (NMI) is calculated for two communities i in the first partition and j in the second partition, according to $\frac{-2\sum_{ij} N_{ij} ln(N_{ij} N/N_i N_j)}{\sum_i (N_i ln(N_i/N)) + \sum_j (N_j ln(N_j/N))}$, where N_{ij} is the number of nodes found in community i of the first partition and community j of the second partition. N is the total number of nodes and N_i and N_j denote respectively the total number of nodes in community i of the first partition and j of the second partition.

[12]This decision is based upon the modularity statistic only. The second best alternative suggested by the leading eigenvector algorithm for the directed network differs in one notable aspect. It distinguishes a separate block of innovations focused on transport and storage (ISIC 630) and lifting and handling equipment (ISIC 29220). In the best partition, these industries are contained within the community centered on automotive vehicles and land transportation (see Table 5).

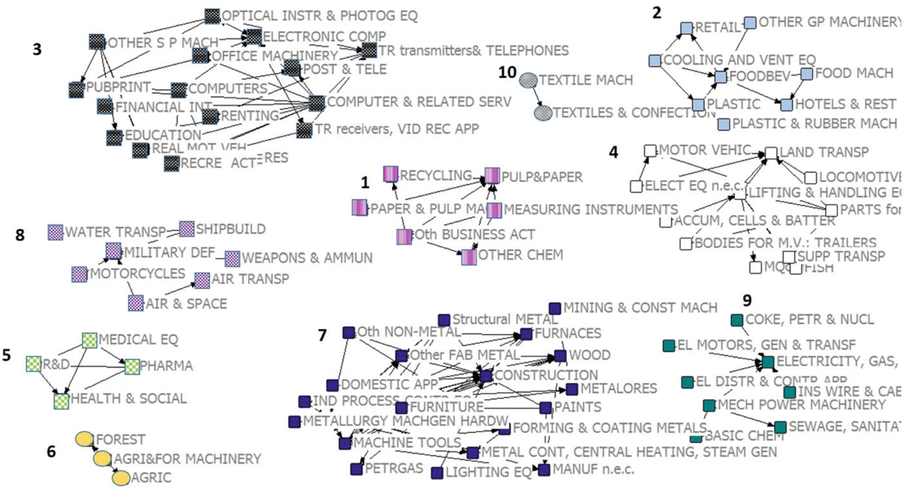


Fig. 3 Communities suggested by fast greedy algorithm. The communities are: (1) Pulp and paper, (2) Food products and packaging, (3) ICT innovations, (4) Automotive vehicles and land transportation, (5) Medical, (6) Forestry, (7) Construction, metals and wood, (8) Shipbuilding, aircraft and military defense, (9) Electricity and (10) Textiles and clothing

The communities are depicted as networks in Fig. 3, which highlights flows of innovations within the communities. A more detailed picture of the industries contained in the communities is also given in Appendix A. The revealed community structure is to a large extent consistent with previous research on Swedish innovation activity and previous descriptions of important interindustry linkages and interdependencies.[13] Thus, these results arguably corroborate previous notions of technological subsystems.

The ICT community (community 3 in Table 5) can be understood as composed of three components. During the first half of the period industries surrounding factory automation were expanding, consisting of computer innovations (ISIC 30020), control systems (ISIC 333) and electronic components (ISIC 321) (Carlsson 1995). The community also reveals that, during this period, a large share of computer innovations (ISIC 30020), together with office equipment innovations (ISIC 30010), was aimed at applications in publishing and printing (ISIC 220). During the second half of the period, ICT innovations were developed for use in electronic components (ISIC 321) and telecommunication services (ISIC 640). These innovations were strongly connected to the deployment of Internet and telecommunications. The ICT community also spans a broad set of user sectors, such as education and financial intermediation,

[13]There are very few outliers, if any, in the communities suggested. Some user industries may appear loosely connected to the communities. For instance, education or financial intermediation in the ICT community or fishing in the automotive community. But these represent relatively important user industries of the core input of the community: computers and ICT products (e.g. software) were often developed for use in schools or banks, and several lifting and handling equipment innovations were developed for fishing.

which were sectors in which computers and other ICT products (such as, e.g., security software) were often directed.

Community 5 spans medical equipment innovations, pharmaceuticals, health care and the research and development sector. This community corresponds well to what has been referred to as the medical and biotechnology ”cluster” or ”technological system” in previous research (Stankiewicz 1997; Backlund et al. 2000). However, biotechnology innovations also include parts of the foodstuff and agricultural innovations.

A broad and important community of innovations (community 7) was formed around the construction and mining sectors and materials for construction purposes, e.g. wood products, metals and fabricated metals, rubber and other non-metallic mineral products. This community also involves machinery for construction and mining, machine-tools and machinery for the processing of wood products and metals.

The remaining communities found were made up of supply industries more or less concentrated on one or two specific user industries: the pulp and paper industry (community 1), food products (community 2), automotive vehicles and land transportation (community 4), forestry (community 6), shipbuilding and military defense (community 8), electricity production and distribution (community 9) and textiles and clothing (community 10). The pulp and paper community (1) consists of chemicals, recycling innovations and technical consultancy innovations, often focused on resolving environmental problems in the paper and pulp industry (see e.g. Söderholm 2009; Karlsson 2012). The community centered on foodstuff (2) has involved plastic innovations, cooling and ventilation machinery innovations and methods for food preparation, and captures the interdependencies between packaging producers (notably Tetra Pak) and the foodstuff industry. The community centered on land transportation (4) mainly consists of automotive innovations and parts for automotive cars, including batteries and electrical apparatus. Suppliers of automotive parts (e.g. Autoliv) and automotive producers (such as Volvo Personvagnar and Saab/Saab Automobile) have formed the basis of strong interdependencies in the development of new technologies (Elsässer 1995). An important part of this community is also centered on the development of electric cars, hybrid technologies and catalytic emission control technologies. The community also involves railway and tramway locomotives and lifting and handling equipment. The community surrounding shipbuilding and military defense (8) informs of strong traditional industrial linkages between the supply of ships, aircraft and weapons to military defense purposes. Swedish shipbuilding and aircraft innovations were the subject of public procurement from the military sector. Both the shipbuilding industry and, the aircraft industry, since its inception in the 1930s, have had strong industrial ties to military defense purposes (see e.g. Eliasson 2010). The community centered on electricity distribution (9) mainly involves electrical apparatus, electrical motors and innovations for heating. Finally, two smaller communities were centered on textiles and clothing (10), involving a small number of textile machinery innovations, and agricultural and forestry machinery (6). The latter community has been strongly focused on the problems arising from the shortage of wood during the 1970s (see Section 4.5.4).

4.3 Supplier and user industries in the network of innovations

Additional insights on the community structure can be obtained through analysis of the relative roles of industries as suppliers and users of innovations. Specifically, this can be studied by comparing the out-strength of industries with the in-strength of industries. The former is defined as the column sums of the innovation matrix

$$k_i^{out} = \sum_j W_{ij} \tag{3a}$$

and the latter as the row sums

$$k_j^{in} = \sum_i W_{ij} \tag{3b}$$

An overall comparison of the out- and in-strength of industries is presented in Fig. 4. The distribution of industries display a tendency to appear along the vertical and horizontal axes rather than being distributed along the line $k_i^{out} = k_i^{in}$. This indicates a strong asymmetry among the industries, suggesting that supplier industries are not typically also user industries to an equal extent, and the converse.

This result also holds within the ten communities detected. They appear to be composed by a set of relatively strong supplier industries supplying innovations to a set of user industries. To distinguish formally between supplier and user industries within communities, the out and in-strengths within communities are employed, calculated respectively as

$$\sum_j \left(k_i^{out}\right) \delta_{c_i c_j} \tag{4a}$$

and

$$\sum_j \left(k_i^{in}\right) \delta_{c_i c_j} \tag{4b}$$

where $\delta_{c_i c_j}$ as before is the Kronecker delta.

Full display of the industry roles in the ten communities is given in Appendix A. In Fig. 5, the industry roles are illustrated for four communities. The color grey indicates industries for which in-strength are less than out-strength and black indicates

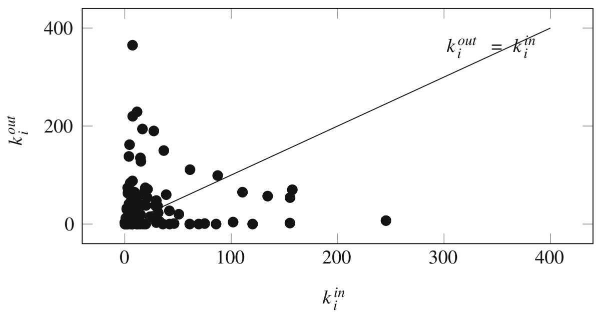
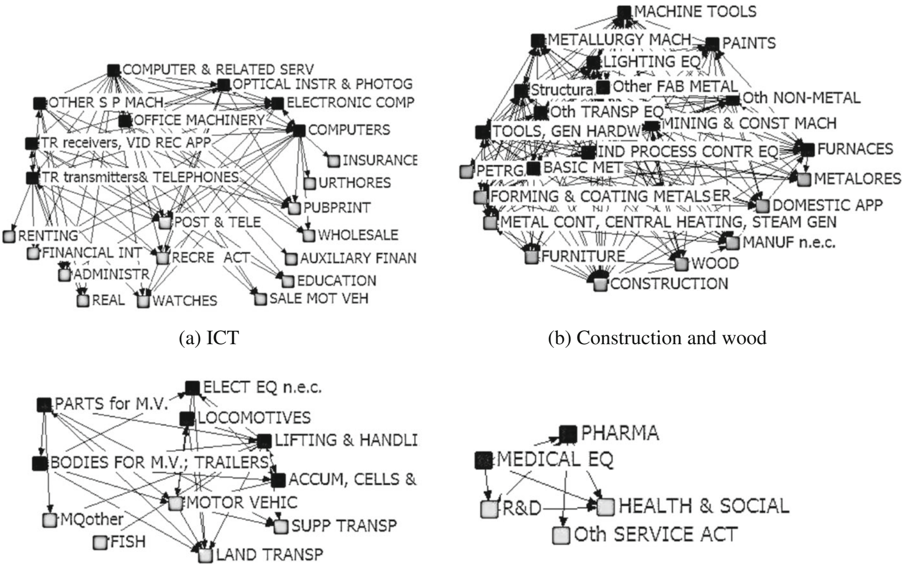


Fig. 4 In-strength and out-strength of innovations in 98 industries, 1970–2007



(a) ICT

(b) Construction and wood

(c)Automotive and land transportation

(d)Medical and pharmaceuticals

Fig. 5 Supply and user industries in the ICT and construction communities

industries for which out-strength exceed in-strength. The ICT community consists of a set of supplier industries, notably hardware electronic equipment, such as computers, software, telephones and electronic components supplying innovations to a broad set of user industries, reflecting the generic diffusion of ICT technologies. The construction and wood community likewise consists of a set of supplier industries, notably machine tools, basic metals, paints and industrial process and control equipment, supplying innovations to the construction, wood and furniture industries. In smaller communities, the asymmetrical supply-use structure of innovation flows is even more apparent. Strong forward links exist between suppliers such as automotive parts, accumulators and batteries and lifting and handling equipment and user industries motor vehicles and land transportation. Medical equipment and pharmaceuticals are the main suppliers to R&D and health and social services.

4.4 Community evolution

In the previous sections, the overall patterns of supply and use of innovations across industries have been described in terms of a partition into communities for the period 1970–2007. The longitudinal dimension of the SWINNO database however also makes it possible to obtain further insights into the evolution of communities over time. A resolution limit of modularity maximizing methods poses a particular problem in this context (Fortunato and Barthélemy 2007) (see footnote 10). To limit the impact of reducing the number of observations studied and for ease of exposition the analysis below compares two sub-periods, 1970–1989 and 1990–2007. Given two snapshot networks of innovations W_{ij} and W^*_{ij}, we can partition the set of industries into communities keeping with the modularity approach. The communities are sets of industries denoted $\mathcal{C}_\mu$ for the first period and $\mathcal{C}^*_\nu$ for the second, where indices μ and ν represent a particular community for the first and second period respectively.

The relations between communities over time is then analyzed in terms of the overlap between any communities $\mathcal{C}_\mu$ in the first period and $\mathcal{C}^*_\nu$ in the second. In our weighted network, the overlap is appropriately defined on the basis of the number of innovations that an industry has within a community, rather than on the number of industries two communities have in common. The overlap measure $\mathcal{O}$ is then a normalized measure based on how many innovations the common industries of $\mathcal{C}_\mu$ and $\mathcal{C}^*_\nu$ would account for in the total count of innovations of $\mathcal{C}_\mu$ and $\mathcal{C}^*_\nu$:

$$\mathcal{O}\left(\mathcal{C}_\mu, \mathcal{C}^*_\nu\right) = \frac{\sum_{i,j\in\mathcal{C}_\mu\cap\mathcal{C}^*_\nu}\left(W_{ij} + W^*_{ij}\right)}{\sum_{i,j\in\mathcal{C}_\mu} W_{ij} + \sum_{i,j\in\mathcal{C}^*_\nu} W^*_{ij}} \tag{5}$$

The overlap thus informs us of the share of innovations for which the common industries of $\mathcal{C}_\mu$ and $\mathcal{C}^*_\nu$ account. With this overlap measure, several relations between communities can be distinguished. Following Spiliopoulou et al. (2006), Wang (2012) and others, a community $\mathcal{C}^*_\nu$ can be defined as a successor of a community $\mathcal{C}_\mu$ if it has the maximum overlap with $\mathcal{C}_\mu$. Conversely, a community $\mathcal{C}_\mu$ is a predecessor of $\mathcal{C}^*_\nu$ if $\mathcal{C}_\mu$ is the community with the maximum overlap with $\mathcal{C}^*_\nu$. We say that $\mathcal{C}^*_\nu$ is a *continuation* of $\mathcal{C}_\mu$ if $\mathcal{C}_\mu$ is a predecessor of $\mathcal{C}^*_\nu$ and $\mathcal{C}^*_\nu$ is also the successor of $\mathcal{C}_\mu$.

From this analysis, we thus obtain pairs of communities that are continuations K. It is here submitted that the strength of the continuations is appropriately measured in a global statistic expressing the share of innovations in the overlap of all the continuations in the total number of innovations of the communities. The total overlap $\mathcal{T}$ is specified accordingly as

$$\mathcal{T} = \frac{\sum_{\mu,\nu}\left(\sum_{i,j\in\mathcal{C}_\mu\cap\mathcal{C}^*_\nu}(W_{ij} + W^*_{ij})\delta_{K_\mu,K_\nu}\right)}{\sum_{\mu,\nu}\left(\sum_{i,j\in\mathcal{C}_\mu} W_{ij} + \sum_{i,j\in\mathcal{C}^*_\nu} W^*_{ij}\right)} \tag{6}$$

where δ is the Kronecker delta. The expression δ_{K_μ,K_ν} has value 1 if μ and ν belong to the same continuation, otherwise 0.

This analysis has been performed using the fast greedy algorithm which gave a partitioning of communities for the matrix of innovations for 1970–1989 and 1990–2007 respectively. These were matched following the procedure of determining the overlap maxima between communities. The results from this analysis indicate a rather stable community structure between the periods 1970–1989 and 1990–2007 as indicated by Fig. 6 and Table 6. Of the nine communities detected in the first period, seven were matched to a continuation in the second period. The average overlap among the continuations was 0.67. The total overlap expresses that 61%

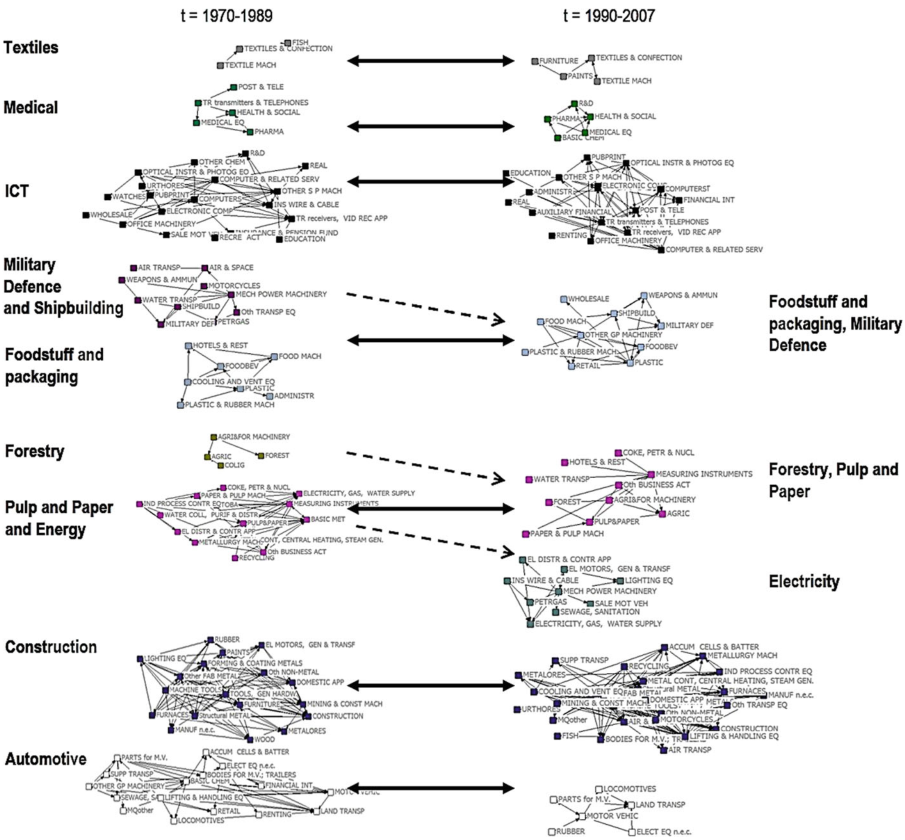


Fig. 6 Evolution of communities between 1970–1989 and 1990–2007. The communities are labelled according to the industry that has supplied or used the largest number of innovations. Double-headed arrows imply that a community in 1990–2007 is a continuation of the community in 1970–1989. Dashed arrow implies a successor or predecessor relationship between the communities

of the innovations were supplied or used by industries that are present in both the community 1970–1989 and its continuation in 1990–2007.[14]

Apart from the fact that the overall community structure appears to be stable, the results point to some further insights into the patterns of innovation over time. One may highlight the close connections between pulp and paper and energy innovations, as well as forestry. In the 1970s and 1980s the pulp and paper industry as well as the steel industry struggled with the overcoming of energy related problems (see Section 4.5.3), which required and induced process and product innovations

[14]The normalized mutual information (NMI) of 0.40 between the partitions must also be assessed as indicating a stable community structure. However, it is based solely on the number of industries within communities and does not take into account that industries that move between communities may have very few innovations.

Table 6 Community partitions for two sub-periods

	1970–1989	1990–2007
Modularity	0.35	0.37
N. communities	9	8
Mean size	10.33	11.63
NMI		0.40
N. continuations		7
Mean overlap ($\mathcal{O}$)		0.67 [0.15]
Total overlap ($\mathcal{T}$)		0.61

to decrease negative environmental impact. Moreover, while the number of forestry innovations plummeted in the second period, the forestry sector has maintained innovation links with the pulp and paper industries. The merging of food products and packaging (1970–1989) with military defense and shipbuilding (1970–1989) expresses a shared dependence of these sectors on measuring equipment innovations. However, in this case the merging is likely due to low resolution as innovation counts were shrinking in the military and shipbuilding industries towards the second half of the period. Observable also is a shrinking of the community centered on automotive vehicles and land transportation, which in the 1970s and 1980s also encompassed lifting and handling equipment. The diminution of this community is explicable by a shift in the dominating application of lifting and handling equipment innovations from transportation to the construction and mining industries.

4.5 Development blocks in the Swedish manufacturing industry

What do the communities found convey about evolving interdependencies between industries and technologies? I have argued that communities may be understood as Dahménian development blocks when incentives for innovation arise from complementarities and the resolution of technological imbalances and obstacles that emerge in technological development. An overall view of the qualitative character of the interdependencies in communities is given in Table 7, which shows the count of innovations exploiting new technological opportunities and problem-solving innovations, by community. The table counts all innovations involved in the community, including innovations for final consumption and general purpose. It is clear from this description that some of these communities have been more centered on the exploitation of opportunities and others more on the solution of techno-economic problems. Some communities consist to a greater extent of innovations exploiting technological opportunities. In particular, this applies to the ICT community and the community centered on medical equipment and pharmaceuticals, where technological opportunities arising from advances in microelectronics, automation, computerization and digitalization or advances in medical sciences and biotech have been salient driving forces to innovation.

Four communities emerge as more focused on techno-economic problems than opportunities: the forestry community, the community centered on construction and

Table 7 Count of innovations involved in communities (including innovations for general purpose innovations and final consumption) divided by origin in problem-solving (PS) and technological opportunities (TO)

Community	TO	PS	TO and/or PS	Total count
1. Pulp and paper	148	114	213	324
2. Foodstuff	70	96	144	303
3. ICT	378	206	480	715
4. Automotive	90	116	176	329
5. Medical	93	35	104	135
6. Forestry	7	29	33	55
7. Construction	154	233	345	642
8. Military defense and shipbuilding	21	8	27	69
9. Electricity	55	68	100	172
10. Textiles	13	15	24	44
Total	1029	920	1646	2788

metal and wood production, the community centered on automotive vehicles and land transportation, and the community centered on electrical apparatus and energy distribution.

Table 7, however, also shows that in most of the communities found, innovation activity has been spurred not only by the exploitation of new technological opportunities but to a significant extent by problems. To appraise the character of innovation interdependencies, a description of the history of imbalances and opportunities is desirable. Therefore the remainder of this study describes the technological imbalances that have provided incentives to innovation, in order to discuss the underlying dynamics in Dahménian development blocks. These descriptions are based on explicit textual descriptions from the journal articles.

4.5.1 Overview

A first observation is that the technological imbalances found vary in character across industries and over time. The imbalances and problems found through a qualitative analysis are summarized in Table 8. On the basis of qualitative evidence presented below, innovation in most of the communities can be characterized as responses to imbalances and opportunities. Such evidence is presented below for the communities surrounding pulp and paper (1), ICT (3), medical equipment (4), forestry (6) and electricity (9) and summarized in Table 8. Though not presented in detail, several innovations in the foodstuff community (2) were centered on resolving problems that appeared in the 1970s in enabling and making use of quick-frozen food technologies (see Taalbi 2014, pp. 229–230). The remaining communities do not however convey the impression of being centered on resolving technological imbalances. A closer study of individual innovations rather conveys that the communities military defense and shipbuilding (8) and textiles (10) were reflecting production linkages. Innovations in the community centered on construction (7) were to a large extent

Table 8 Innovations centered on solving imbalances, 1970–2007

Innovations	Community	Imbalances (summary)
Chlorine free bleaching processes	1. Pulp and paper	Replacement of chlorine
Quick-frozen food	2. Foodstuff	E.g. bacteria in thawing, temperature in distribution
Automated guided vehicles	3. ICT	Insufficient capacities of control systems
Laminate for electronic components	3. ICT	Under-etching
Secure payment and secure identification	3. ICT	Security issues in Internet networks
Telecommunication and Internet networks	3. ICT	Capacity requirements of network standards
Emission control technology	4. Automotive	Availability of unleaded fuels, Technical problems in catalytic converters
Electric and hybrid electric cars	4. Automotive	Weight and energy density of batteries
Pharmaceuticals and drug screening	5. Medical	E.g. slow drug screening, incapacity to deal with vast amounts of data
Forestry deforestation methods	6. Forestry	Unprofitability, obstacles to rational production methods
Occupational noise	7. Construction	Technical difficulties in reducing vibrations
Offshore exploitation of resources in the North Sea	8. Military defense and shipbuilding	Rough climate, maintenance of oil rigs
Nuclear power	9. Electricity	Security
Speed control of AC motors	9. Electricity	Speed control
Solar power (solar collectors and solar cells)	Several	Limited sun exposure, cost structure
Heat pumps	Several	Technical construction problems

problem-solving, e.g. being developed to address health issues such as occupational noise. This case could however not be characterized a typical development block, but is more likely to have reflected strong interdependencies in the supply chain that have been important channels for problem-solving activities.

A second observation is that many of the communities found can be broadly understood as related to two macro-economic problem complexes: 1) imbalances emerging in the ICT technology shift, and 2) imbalances emerging in the attempts to deal with the adverse environmental and societal effects of oil based technologies and production systems. For reasons of space the discussion is summarized in terms of problems and opportunities pertaining to these two macro-economic problem complexes: the microelectronics revolution (pertaining to the ICT community) and the environmental imbalances that appeared following the oil crises of the 1970s (pertaining to communities pulp and paper, automotive and electricity). Two special cases are briefly discussed: pharmaceuticals (the medical community) and the Swedish forestry industry. See Taalbi (2014) for an in-depth description and industries not discussed in the present work.

4.5.2 ICT

The first type of imbalances are most notably found in factory automation during the 1970s and 1980s and in the numerous telecommunication innovations that were aimed to resolve capacity bottlenecks in the emerging telecommunication networks during the 1990s. These development blocks were primarily contained in the ICT community.

Similar to the cases of the steam engine, the dynamo and electricity, the breakthrough of microelectronics was preceded by several decades of discovery and improvement of electronic components and computers. Major breakthroughs in electronics were made with the digital computer (1945), the transistor (1947) and integrated circuits (1961). These innovations resulted from attempts to overcome bottlenecks, high assembly costs and rising complexity of transistor-based systems, what has been called the "tyranny of numbers".

Thus, in the early 1970s an imbalance was being resolved by the exploitation of micro-electronics. Though Sweden was not a large supplier of electronic components, a small number of innovations can be observed aiming to solve critical problems in the production and use of electronic components during the 1970s, such as under-etching, problems in detecting manufacturing errors due to overheating, and overcoming bottlenecks in the production of electronic components, such as the manufacturing of masks. Meanwhile, a development block surrounding factory automation emerged, primarily driven by the exploitation of new opportunities from the now unleashed capacity of microprocessors. In Sweden, this was a strong development block involving a large set of actors producing micro-computer based control systems, industrial robots, machine tools and automated guided vehicles (Carlsson 1995; see Taalbi 2014, pp. 101–106). Examples of innovations aimed to compete and reach new areas of application by improving the performance of control systems and automation equipment are abundant in the SWINNO database.

Not only technological opportunities, but also technological imbalances have however occasionally emerged between the capacity of control systems and the requirements of applied technology. In such cases the development of micro-electronics enabled the solution of technological imbalances in the 1970s. For instance, the introduction and further development of automated guided vehicles (AGV) can be described in this way. The first AGV was commercialized by the US company Barret Electronics in the 1950s. A hampering factor in the development of AGVs was however the limited capabilities and bulkiness of the control systems for the guidance of the vehicles. Solutions to these problems were made possible by the advancement of integrated circuits and microelectronics. One example of a Swedish firm attacking these imbalance is Netzler and Dahlgren (NDC), emerging as one of the pioneers in the development of AGV control systems when it became involved in a Volvo project, the first installation of AGVs in Sweden.[15] Also the further development of AGVs has been characterized by the overcoming of critical problems. The guide paths were perceived as inefficient and expensive when the users wanted to modify the trucks' movement patterns and several innovations were developed during the 1980s and 1990s aiming to attain flexibility in this way, by e.g. using laser navigation technologies.

The major imbalances observed in the broader ICT development block appeared later in the many technological obstacles facing the deployment of Internet and telecommunication networks during the 1990s and 2000s. A primary driving force in the development of telecommunications and in the deployment of Internet technology has thus been the emerging imbalances between network components, such as circuits and switches, and the network requirements. Such problem-solving innovations included transmission systems and transmission technologies, network switches and electronic components for data and telecommunication networks. Most of these innovations can be understood as responding to obstacles in the introduction of new communication technologies, such as broadband access technologies DSL (Digital Subscriber Line) and the telecommunication transmission standard, ATM (Asynchronous Transfer Mode) or in the later introduction of Voice-over-IP (VoIP). For example, the development of ADSL technology (Asymmetric Digital Subscriber Line) commenced internationally to address a capacity bottleneck (Fransman 2001, pp. 125–126). Moreover, when Swedish Telia was the first in the world to transmit high resolution TV images using VDSL (Very high speed Digital Subscriber Line), it was noted that modems and network components were necessary for a commercially functioning technology. In 1999, Telia Research could launch a series of chips adapted for VDSL, developed together with the French chip manufacturer ST Microelectronics. Similarly, ATM (Asynchronous Transfer Mode) was developed to fulfil the requirements of broadband, enabling digital transmission of data, speech and video and to unify telecommunication and computer networks. For this technology, fast circuits were needed. Ericsson developed an ATM circuit, AXD 301 for broadband networks aimed to increase performance and fulfil security requirements. Netcore (later renamed Switchcore) launched a circuit that could handle both ATM and IP technology. With increased traffic, the data switch was a capacity bottleneck, but with Netcore's circuit it became possible to build faster and cheaper switches.

Other imbalances can also be found among ICT industries. Internet and data communication security was an imbalance that spurred innovation activity, in particular during the 1990s and 2000s. For example, the breakthrough of ”e-commerce” was considered to be hampered by the problem of attaining secure transactions. Other

[15] In 1972, NDC developed the control system for Volvo's carriers. As a result of the project Volvo developed and commercialized its carrier technology, for instance at Tetra Pak. NDC was also involved in developing the computerized control system in this project. A subsidiary to Volvo, ACS (AutoCarrier System), was formed in 1976, based on a guided carrier, the so-called Tetracarrier.

firms developed systems for secure identification on-line or in mobile phones, selling their services to banks.

4.5.3 Innovations pertaining to environmental imbalances

The second set of imbalances concerns the production of energy and environmental problems, concentrated in particular in the pulp and paper and the automotive communities. Following the oil crises of the 1970s, search *en masse* for new energy technologies was initiated. Some examples of energy technologies developed during this period were heating pumps, innovations for the use of biomass (e.g. wood and forest residue) and peat, and innovations for the use of solar and wind power. These were all technologies characterized by their own obstacles, which frequently focused the direction of innovation activity. Accordingly, several innovations were developed aiming to overcome techno-economic obstacles to the use of various forms of bio-energy, e.g. forest residue, peat and recycled biological waste, aimed to break oil dependency. Wood and forest residue was one of the main alternative fuels. An urge to make better use of wood material was occasioned by a wood shortage during the 1970s and worsened by the growing demand for chips for energy production. This led to the development of new methods and machinery that attempted to overcome obstacles to attain profitability in the processing of forest residue. Other alternative energy sources were also increasingly explored from the 1970s by solving critical problems. For instance, obstacles to the use of solar energy spurred innovation activity from the 1970s. Many of these were developed in order to enable seasonal and long term storage of summer excess energy. In fact, chemical energy storage was still by the end of the period a problem that, together with renewed interest in solar-power, induced Swedish innovations.

Other innovations have been aimed at dealing with negative externalities and industrial waste. The alleviation of the paper and pulp industry's environmental problems has involved not only new production processes, but also new paper and pulp machinery, measuring apparatus and new chemicals. Swedish firms have been pioneers in producing biofuel from residue from the pulp and paper industry. These innovations have aimed both at solving environmental problems and reducing production bottlenecks, such as the costly recovery boilers. Some innovations were aimed to produce biofuel from residue from the pulp and paper industry. For instance, the Chemrec process (developed by a firm with the same name) was aimed at replacing the recovery boilers and enable increased energy efficiency. Some other innovations were developed to replace traditional chlorine bleaching processes, often induced by new regulation. With the Swedish Environmental Protection Act of 1969, efforts were directed towards reducing emissions and developing new processes for bleaching of pulp residue. So it was that, during the 1970s, oxygen bleaching processes were developed in Sweden (e.g. by firms MoDo and Kamyr). At the time main chlorine free alternatives were oxygen bleaching and chlorine dioxide bleaching. From the end of the 1980s the industrial emissions of absorbable organic halogens (AOX) were regulated, which meant a push into technology development. For example, as a response to regulations of AOX, Eka Nobel developed its Lignox method, a chlorine free bleaching process based on hydrogen peroxide.

The adverse effects of emission and vehicle exhaust form an imbalance at the core of the community centered on automotive engines, batteries, automotive vehicles and land transportation. One may point at two parts of this development block. The first part, encompassing a larger number of innovations, is centered on emission control technology and innovations introduced to decrease vehicle exhausts for gasoline driven vehicles. To a non-negligible extent the increased oil, fuel and energy prices in the 1970s forced the automotive industry to concentrate efforts in this direction. In addition, consumer demand, environmental awareness and sharpened environmental laws have since then also driven technological development in this direction (Elsässer 1995). The development of catalytic converters and emission control technologies can be described as characterized by the successive overcoming of technical problems, frequently developed in response to the introduction of exhaust requirements and legislation.[16] Examples in point relate to EGR (Exhaust Gas Recirculation), developed in the US as a response to stricter NO_x limits during the 1970s. Swedish firms have since integrated the technology into cars. Towards the 1990s and 2000s some Swedish innovators developed the technology further, spurred by the continued sharpening of emission standards. For instance, a critical problem with EGR has been that the exhaust gases have a lower pressure than the fresh air, which leads to increased fuel consumption. This problem was solved by two inventors starting up a new company, Varivent, later bought by Haldex.

The development of hybrid and electric cars and trucks, and the complementary development of automotive engines, batteries and battery stations make up the second part of the automotive community. Such innovations have been instrumental in the development of more fuel efficient and environmentally friendly cars and transport vehicles. The development of hybrid and electric cars has prompted other complementary innovations, due to well-known bottlenecks. Most importantly, the difficulties in developing sufficiently light and energy-dense batteries with sufficient life length have been salient critical problems and have hampered the commercialization of electric and hybrid cars for decades. Several Swedish innovations were, therefore, aimed at ameliorating or solving such problems, among other things batteries with longer life length, charging stations and hybrid technologies (see Taalbi 2014, pp. 220–224) for further examples).

4.5.4 Forestry

The forestry community describes innovations responding to a problem complex, which emerged from a strong negative pressure during the structural crisis of the 1970s. These innovations illustrate a quick industrial response in terms of innovation to a common crisis. Problems in the forestry sector became severe when an acute wood shortage broke out during the 1970s when both production shrank and prices were kept low despite high demand. In 1974 the yearly deforestation level

[16] For instance in response to US regulations, Saab-Scania and Volvo separately developed three-way catalytic converters (TWC), introduced in new car models for the US market in 1976 (Elsässer 1995; Bauner 2007, pp. 254–255).

of the forestry industry reached the maximum level allowed by Swedish legislation. Taken together, these conditions influenced a number of forestry machinery innovations aimed to enable better wood usage per tree felled. Accordingly, these problem-solving innovation can be understood as a block of innovations aimed to make profitable culling and handling of wood and to eliminate obstacles hindering the introduction of rational production methods, such as whole tree deforestation.

4.5.5 Pharmaceuticals and drug screening

Other imbalances are indicated by a set of cases in the medical community. Innovations in the community centered on medical equipment and health care were, for the most part, driven by advances in microelectronics or scientific advances in biotechnology and medicine. The community, however, contains a set of innovations centered on pharmaceuticals and drug screening that have been spurred by a sequence of technological imbalances. According to Nightingale (2000) and Nightingale and Mahdi (2006), there were three main imbalances in the development of pharmaceuticals. One of the main imbalances was the slow screening of molecules, which was overcome by the introduction of throughput screening in the 1990s. Up until then a number of innovations were developed in Sweden exploiting microelectronics to enable faster screening. The overcoming of the slow screening bottleneck however created a new imbalance in the synthesis of chemicals. The pharmaceutical companies could not develop new interesting substances at a sufficiently fast rate and were therefore deploying resources into finding automated processes for chemical synthesis. One Swedish example was a firm, Pyrosequencing, which developed a process for DNA sequencing based on a new method developed at the Royal Institute of Technology. Another firm, Cellectricon, developed innovations to attack similar critical problems in drug screening and development of new drug candidates. Cellectricon's ”Dynaflow” process automated the drug screening process by way of a ”micro-shower” for cells.

The introduction of automated synthesis of large amounts of chemicals however also created a new imbalance in the inability of firms to handle the large amounts of data. During the second half of the period the advances made in computer programming could be exploited to solve technical problems in areas such as pharmaceutical production and genetic engineering. An example was a firm, Visual Bioinformatics, that responded to the problem of handling large amounts of experimental data by developing an analysis program to analyze and visualize data.

5 Conclusions

Using a combination of quantitative techniques and qualitative information from innovation biographies, this study has explored the interdependencies in the Swedish network of innovations, 1970–2007. In doing so, the study contributes with a new empirical methodology to examine development blocks and technological interdependencies. By studying simultaneously interdependencies from quantitative and qualitative data, this article is also able to assess aspects of technological systems that previously have mostly been examined in case studies.

The results of this study convey three principal messages. The empirical analysis, first of all, reveals how interdependencies in the Swedish network of supply and use of innovations can be described in terms of ten communities: pulp and paper, foodstuff, ICT, automotive vehicles and land transportation, medical equipment, forestry, construction, military defense, aircraft and shipbuilding, electricity and textiles. The statistical and qualitative analyses suggest that several of the communities found were focused on resolving technological imbalances, either under a pressure to transform, as in the pulp and paper or forestry industries, or a positive situation, as in the telecommunication industries during the 1990s. For seven of the ten communities, the innovations involved were parts of smaller or broader development blocks centered on the exploitation of new technologies or the overcoming of technological imbalances. For the communities surrounding military defense, aircraft and shipbuilding, textiles and construction, the community structure was rather more likely to reflect strong production linkages. These results suggest that the innovation dynamics, the driving forces of innovation in particular, may vary considerably among sets of interdependent industries. The community surrounding military defense, aircraft and shipbuilding was, for instance, strongly driven by public procurement, and the community surrounding construction by supplier-user interactions and strong production linkages. By contrast, the ICT and medical development blocks have been considerably dynamic: innovations have to a significant extent found driving forces in technological imbalances or opportunities created through advances elsewhere in the development block.

Second, the empirical analysis has also revealed that, overall, the Swedish network of innovations displays a highly asymmetrical structure as regards the supply and use of innovations. Moreover, the structure of the network indicates that linkages between industries to a large extent can be understood in terms of vertical relations between suppliers and users. The observations on the importance of vertical relations between suppliers and users as well as the importance of innovation as a problem-solving activity match well with the notion that supplier industries have typically solved problems emerging in user industries (Rosenberg 1969; Lundvall 1988). These results appear to stress the role of producer-user interactions in shaping the structure of supply and use of innovations. This certainly could be further studied in the context of IFMs, investigating the role played by users in directing focus of innovation towards particular problems.

A third result of this study is that communities have been rather stable, though the nature of technological imbalances driving innovation has shifted considerably over time. The analysis of the evolution of communities in Section 4.4 indicates that most of the communities found have been remarkably stable over the period studied, suggesting that the structure of inter-sectoral patterns of innovation are, to a considerable extent, of long-term duration. This result further points to the existence of underlying proximities, e.g., relatedness in knowledge base and production linkages, that are likely to shape innovational interdependencies and to act as focusing devices for problem-solving or opportunity recognition, something which should be investigated further through comparison of inter-industrial flows of innovation and economic interdependencies (compare DeBresson 1991).

Yet, the qualitative character of innovation has changed considerably over time and is intrinsically linked to the broader economic history of the Swedish industry. In terms of the imbalances solved by innovations, many of the communities found can be broadly understood as related to two macro-economic problem complexes: 1) imbalances emerging in the ICT technology shift, and 2) imbalances emerging in the attempts to deal with the adverse environmental and societal effects of oil-based technologies and production systems. The imbalances found in the development block surrounding ICT have moved from being geared towards obstacles to the exploitation of micro-electronics in the 1970s, to obstacles that appeared in the deployment of Internet and telecommunication networks in the 1990s. Other technologies have struggled with imbalances characterizing a development block in formative phases. A case in point is the electric car, which has for a long time struggled with the difficulties of attaining longer driving ranges and attaining sufficiently light and energy dense batteries. Another is the development of technologies for the use solar energy, which has struggled e.g. with attaining seasonal and long term storage of energy. As these major imbalances are being solved, both of these development blocks are, it would seem, now passing into a phase of wider diffusion (in which, however, other imbalances may emerge). These empirical observations are consistent with the view, suggested by several authors, that the type of problems or imbalances that require investment or innovation varies along the life cycle of development blocks or technological systems (Hughes 1983; Schön 1991; Freeman and Louça 2001). From this perspective, though innovational interdependencies may be stable in terms of the industries that are strongly interdependent, the successful overcoming of imbalances may require different technological, institutional or political arrangements, depending on the types of imbalances that drive the evolution of development blocks. Thus, ”imbalance” appears to be a keyword for understanding the evolution of technologies and the potential role played by institutions and policies in that process, in particular, as missing complementarities may obstruct the emergence of new development blocks (cf. Markard and Hoffmann 2016).

However, several aspects in the evolution of interdependencies between technologies and industries are yet to be understood. One is the question of what precisely shapes the different types of dynamics found across communities. Research along such lines should certainly find rewarding the study of the interplay between, e.g., production linkages, geographical externalities and knowledge and innovation flows. In particular, one interesting avenue for further research should certainly be to examine to what extent other proximities, such as knowledge and production linkages, both determine and are determined by innovational interdependencies over the course of the life cycle of development blocks. Such research endeavors would be aided by the development of improved techniques for dynamic community analysis and by the construction of long-term historical data of innovation flows.

Compliance with Ethical Standards

Conflict of interests The author declares no conflict of interest.

Appendix A: Detailed description of communities

Table 9 Industry roles within the communities found for the IFM 1970–2007. Share of total number of innovations supplied or used within community

Community	Main Suppliers (share of innovations supplied within community)	Main Users (share of innovations used within community)
1. Pulp and paper	Instruments and appliances for measuring, checking, testing, navigating and other (ISIC 332) 42.41%; Machinery for paper and paperboard production (29550) 28.56%; Other business activities (ISIC 740) 18.94%	Pulp, paper and paper products (ISIC 210) 65.55%; Other business activities (ISIC 740) 22.28%
2. Food products	Plastic products (ISIC 252) 30.33%; Machinery for food, beverage and tobacco processing (ISIC 29530) 20.65%; Food products and beverages (ISIC 150) 15.66%; Other general-purpose machinery n.e.c. (ISIC 29240) 14.6%; Non-domestic cooling and ventilation equipment (ISIC 29230) 13.24%	Food products and beverages (ISIC 150) 74.32%
3. ICT innovations	Other special purpose machinery n.e.c. (ISIC 29569) 22%; Computer and related activities (ISIC 720) 20.86%; Electronic valves and tubes and other electronic components (ISIC 321) 12.55%; Computers (ISIC 30020) 10.79%; Optical instruments and photographic equipment (ISIC 334) 10.76%	Publishing, printing and reproduction of recorded media (ISIC 220) 35.08%; Electronic valves and tubes and other electronic components (ISIC 321) 10.38%
4. Automotive vehicles and land transportation	Parts and accessories for motor vehicles and their engines (ISIC 343) 38.14%; Motor vehicles (ISIC 341) 19.99%; Lifting and handling equipment (ISIC 29220) 16.94%; Electrical equipment n.e.c. (ISIC 316) 11.89%	Motor vehicles (ISIC 341) 48.77%; Land transport; transport via pipelines (ISIC 600) 31.29%
5. Medical	Medical and surgical equipment and orthopaedic appliances (ISIC 331) 62%; Pharmaceuticals (ISIC 244) 34.55%	Health and social work (ISIC 850) 87.42%
6. Forestry	Agricultural and forestry machinery (ISIC 293) 94.76%	Forestry (ISIC 20) 76.22%; Agriculture and hunting (ISIC 10) 23.78%
7. Construction, metals and wood	Machine-tools (ISIC 294) 22,25%; Basic metals (ISIC 270) 13.16%; Wood and wood products, except furniture (ISIC 200) 10.91%	Construction (ISIC 450) 36.65%; Wood and wood products, except furniture (ISIC 200) 11.77%; Basic metals (ISIC 270) 10.08%;

Table 9 (continued)

Community	Main Suppliers (share of innovations supplied within community)	Main Users (share of innovations used within community)
8. Shipbuilding, aircraft & military defense	Building and repairing of ships and boats (ISIC 351) 54.49%; Weapons and ammunition (ISIC 296) 21.14%; Aircraft and spacecraft (ISIC 353) 21.06%	Provision of services to the community as a whole (ISIC 752) 63.23%; Water transport (ISIC 610) 21.52%
9. Electricity	Machinery for the production and use of mechanical power, except aircraft (ISIC 291) 43.13%; Electricity distribution and control apparatus (ISIC 312) 21.6%; Electric motors, generators and transformers (ISIC 311) 13.42%; Basic chemicals, pesticides and other agro-chemical products (ISIC 241-242) 11.57%	Electricity, gas, steam and hot water supply (ISIC 400) 56.57%; Sewage and refuse disposal, sanitation and similar activities (ISIC 900) 28.18%
10. Textiles	Machinery for textile, apparel and leather production (ISIC 29540) 90.18%	Textile and clothing (ISIC 170-190) 99.94%

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