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THE KNOWLEDGE BASE IN THE ENGINEERING SECTOR

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INTRODUCTION

The charge in this paper is to develop a set of measures to describe the knowledge base in the engineering sector, its contents, size, and change over time.

The engineering sector is made up of a wide range of industries (including fabricated metal products, industrial machinery and equipment, electronics and other electrical equipment, transportation equipment, and instruments and related products). As a result, the knowledge base of the engineering sector may be viewed as a set of complex and overlapping systems, each focused on a particular (generic) technology or area of economic activity.

In previous work jointly with a group of researchers in Sweden I have defined *'technological systems'* as knowledge and competence networks supporting the development, diffusion and utilization of technology in established or emerging fields of economic activity (Carlsson & Stankiewicz 1991). This notion of technological systems seems particularly appropriate to the problem at hand and will therefore be used throughout this paper. An alternative would be to use a similar concept, that of sectoral systems of innovation (Breschi and Malerba, 1997; see also Malerba and Orsenigo, 1990; 1993; 1995). But I will use the technological systems concept, since I am more familiar with it and have more data readily available.

Previous studies of technological systems by this group of researchers have focused on factory automation, electronics and computers, pharmaceuticals, powder technology, biomedicine and biotechnology, and polymers (see Carlsson 1995, 1997, and 1999). In each case, we have attempted to analyze the evolution of the system by using a general framework that is actually quite similar to that proposed by Foray (1999).

Systems consist of components and/or actors, relationships among these, and their characteristics or attributes. Systems of innovation can be viewed in several dimensions. One is the physical or geographical dimension. Sometimes the focus is on a particular country or region which then determines the geographic boundaries of the system. In other cases the main dimension of interest is a sector or technology. In such cases, the determination of the relevant geographic boundaries becomes an important issue. Due to the vast improvements in communication technology in recent decades, there is an international or global dimension to almost any economic activity. How to delineate a system is therefore an important task: is the supporting knowledge base global or geographically bounded?

Another important question is: what is the appropriate level of analysis for the purpose at hand? It matters, for example, whether we are interested in a certain technology, product, set of related products, a particular cluster of activities or firms, a whole sector such as the engineering sector, or the science and technology base generally. The choice of components and system boundaries depends on this, as does the type of interaction among components to be analyzed. The attributes or features of the system components that come into focus also depend on the choice of level of analysis.

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

The paper is organized as follows. First the contents of the knowledge base and its attributes are discussed. Next, the systems and mechanisms for generating, accessing, and transferring knowledge are examined. This is followed by a review of measures of the performance or effectiveness of the knowledge base. The paper concludes with some final reflections.

CONTENTS AND ATTRIBUTES OF THE KNOWLEDGE BASE

The Contents (Components) of the Knowledge Base

What is the nature and composition of the knowledge base in the engineering sector? Given the wide array of products and technologies involved, it is quite difficult to provide an answer for the sector as a whole. But in the course of our work on technological systems, two members of our group, Anders Granberg and Rikard Stankiewicz, carried out a detailed investigation of the knowledge base which is part of the technological system supporting factory automation in Sweden. This is the system most completely mapped out in our studies of technological systems thus far.[1] Factory automation is defined as the cluster of technologies focused on solving technical problems involving the enhancement, assistance, and substitution of human labor through the use of certain techniques or machines in manufacturing operations. Factory automation is at the heart of the engineering sector and cuts across all its fields and sub-sectors. Even though its knowledge base does not include all the relevant disciplines (such as metallurgy and other materials sciences), it provides a good example of what is involved in describing and analyzing the nature, contents, and complexity of the knowledge base in the engineering sector.

The technological system supporting factory automation in Sweden is defined as the set of actors (suppliers of factory automation hardware and software, user companies, and consulting

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[1] The system is described in detail in Carlsson (1995) and summarized in Carlsson (1997). The knowledge base is mapped out and analyzed in Granberg (1995a and 1995b) and Stankiewicz (1995).

firms) in the commercial/industrial arena, the R&D infrastructure (academic institutions, research institutes, and ‘bridging institutions’ that link these to the business sector), and the policy agencies, both public (especially the National University Board and the National Board for Industrial and Technical Development) and private (e.g. the Engineering Industry Association) which interact to generate, diffuse, and utilize factory automation in Sweden. Factory automation is defined as being made up of the following products (technologies): computer-aided design (CAD), computer-integrated manufacturing (CIM), flexible manufacturing systems (FMS), numerically and computer-numerically controlled (NC and CNC) machine tools, industrial robots, and other automated materials handling equipment.

The knowledge base supporting the users of factory automation (the vast majority of firms throughout the engineering industries) includes management competence, manufacturing competence, and industrial design competence. The major fields represented are the various management disciplines and industrial engineering (including production engineering, systems engineering, control engineering, and software engineering).

The knowledge base supporting suppliers of factory automation consists of the following disciplines: electronic engineering, electrical engineering, mechanical engineering, control engineering, systems engineering, software engineering, and production engineering. The relationships between these fields and the various factory automation products are shown in figure 1. A more detailed breakdown of the major component technologies which make up factory automation and the fields on which they are based is provided in figure 2.

Putting all this together into an overview of the entire factory automation cluster of technologies, a complex picture emerges. See figure 3. Seven major sub-clusters can be identified:

(I) the factory automation core cluster

(II) a socio-technical cluster pertaining to a wide range of problems in conjunction with the acquisition, user adaptation, and operation of factory automation equipment

(III) a general engineering cluster with broad ties to the technical competence base of both suppliers and users

(IV) a sensing/metering cluster of particular relevance to the control problems of factory automation

(V) an ‘information technology’ cluster bearing on the entire spectrum of information-handling problems arising in factory automation

(VI) a physical science-based technological support cluster of direct relevance to the hardware-centered problems addressed by clusters IV and V; and

(VII) a formal science-based cluster providing extensive software and generic-design support to problem-solving in all systems, subsystems, and components (Granberg 1995, pp. 113-114).

Having defined these major clusters, Granberg proceeded to identify the academic units (‘focal units’) representing each field and their linkages to each factory automation core technology. The results are summarized in figure 4. Through interviews with personnel at each academic institution he was able to determine the number and intensity of the connections between these units and each core technology. By aggregating these connections over the seven field clusters, he could then assess the number and intensity of linkages between each field and the focal units, thus obtaining an overall view of the major components of the knowledge base. See figure 5.[1]

Finally, Granberg developed a picture of the entire network of institutional links between the academic units and the various actors in the factory automation field, in academia as well as in industry, also including non-academic research institutes and foreign entities. See figure 6.

Basic Attributes of the Knowledge Base

[1] Figures 4 and 5 provide an overview of the situation ca. 1990. Granberg also developed a rough time line of the technologies, major technical events, and main actors over the preceding two decades to indicate the evolution of the knowledge base over time.

What are the attributes of the knowledge base in the engineering sector which determine the locus of innovation (generation of new ideas) and also the accessibility and transferability of knowledge?

There are several ways to characterize the knowledge base in a sector. One dimension is the *degree of codification of knowledge*. Some areas of knowledge are highly accessible, with well-built access routes and well-established rules and procedures for knowledge transfer. Here knowledge is highly codified. Provided potential users have the proper competence and equipment, they can access the technology. This results in a short distance between the science frontier and best industrial practice. This appears to be the case in the engineering sector. R&D in the industrial firms tends to be oriented towards practical application and integration of ideas throughout their activities, whereas academic research is much more theoretical and discipline-based. At least in the Swedish case, the advanced research capabilities have rested primarily in business firms and in the non-commercial research institutes. Before the 1980s, little research was done on factory automation at the universities, and the curricula lacked a factory automation orientation. The contribution of the educational system was largely confined to the training of engineers rather than research. It was only during the second half of the 1980s that the universities began to play an important role in research in this field.

Another dimension in which the knowledge base can be described is the extent to which knowledge pertains to individual components in a system or has more to do with the architecture or overall design of the system. As described above, factory automation (except computer-integrated manufacturing, CIM) has to be characterized as falling into the component category.

A related dimension is the extent to which knowledge is embodied in equipment, products, etc., versus disembodied. In this dimension, factory automation knowledge is clearly mostly embodied.

Another dimension which has bearing on the locus of knowledge generation and the transferability of knowledge is the nature of the discovery process itself: whether it is design-driven (focused on some particular aspect or application) or experimental. The highly focused (and applied) nature of R&D in the engineering industries makes it more likely for new discoveries to take place in business firms than in universities. In biotechnology, by contrast, the opposite is true: the experimental nature of the discovery process favors location in the universities or other entities (research institutes or technology-based start-ups) rather than in the well-established business firms.

SYSTEMS AND MECHANISMS FOR ACCESSING AND TRANSFERRING KNOWLEDGE

How do business firms in the engineering sector (and factory automation in particular) acquire the knowledge they need? What are the systems and mechanisms involved?

As indicated already (see figures 4, 5, and 6), there are numerous **linkages among the various entities** within the factory automation technological system. The number, frequency, and contents of the contacts depend on a whole variety of factors including physical proximity and the receiver competence (absorptive capacity) of the business units relative to the competence of the knowledge-creating entities.

As discussed above, the **locus of the learning process** (in-house vs. outside) as reflected in R&D activities is determined to a high degree by the nature of knowledge and of the knowledge creation process. In factory automation, the bulk of R&D is carried out by business firms. It is highly focused, practical and application- as well as component-oriented. It often involves learning by doing, mostly by repetition of similar tasks rather than through experimentation.

Two things should be noted about R&D expenditures. One is that R&D expenditures may not be a good indicator of the amount of learning that is taking place. As shown by Laestadius (1998), only about 20 % of the total development costs of new thermopulp technology (for pulp and paper production) was accounted for as R&D in the statistics; the rest was made up of engineering costs and production losses, both jointly between the machine company and the paper & pulp company, and in each company separately. Similar findings have been reported with respect to the development of new machine tools (e.g., Carlsson 1989).

Another thing worth noting is that the total amount of R&D within the system does not necessarily reflect global knowledge-enhancement. To the extent that R&D expenditures of individual firms represent their costs for maintaining or increasing their absorptive capacity as well as identifying the knowledge frontier (as distinct from pushing out the frontier), they do not constitute a net addition to knowledge at the system level.

The horizontal diffusion of knowledge (spillovers) among business entities is difficult to measure but is reflected in the density of the networks in which firms are involved. In cases of high network density (high degree of connectivity), expenditures on R&D yield much higher returns at the system level than in systems with low connectivity. This was illustrated in simulation exercises which also showed the importance of high receiver competence (Carlsson, Eliasson and Taymaz 1997).

Learning from users (customers) is also an important learning mechanism. In each technology within factory automation that we have studied, a key role was played by a lead user or competent buyer: some entity that has the competence required to formulate the technical problem(s) to be solved (see Carlsson and Jacobsson 1991). ABB, Volvo and Saab are examples of such advanced customers in Sweden. Eliasson (1997) goes further and suggests that these advanced buyers can play the role of a technical university within their areas of competence.

Another **learning mechanism** is **via suppliers of equipment and new technologies**. This mechanisms appears not to be important in the engineering sector, at least not in factory automation. One of the reasons for this is that equipment suppliers are generally quite small firms with limited technical capabilities, whereas the customers are often giant firms with much greater and broader capabilities who are also more knowledgeable about the particular problems to be solved.

The use of new information and communication technologies (IT) can also contribute to learning and enhancement of the knowledge base. The density of such technologies per employee or in relation to output can provide a good estimate. See table 1.

Table 1 Density* of Flexible Automation Techniques in Various Countries

Country	NC Machine Tools* (1984)	Industrial Robots (1989)	FMS** (1988)	CAD (1985)
France	n.a.	3.98	n.a.	2.89
W. Germany	11.38	5.84	19.2	2.62
Italy	n.a.	8.57	n.a.	0.31
Japan	22.40	43.50	31.7	0.72
Sweden	**22.18**	**9.35**	**108.1**	**3.76**
U.K.	10.51	2.87	43.7	3.17
USA	11.73	4.64	17.6	6.33

* Number of units per 1,000 employees in the engineering industry (for NCMTs, industrial robots, and FMS) and in the manufacturing sector (for CAD)
** per million employees in the engineering industry

Sources: *Numerically controlled (NC) machine tools*: Edquist and Jacobsson (1988), p. 104. *Industrial robots:* Karlsson (1991) and OECD (1989). *FMS:* Ranta (n.d.) and OECD (1989). *CAD:* Åstebro (1991).

A final measure of the knowledge base proposed in Foray’s paper is **the aggregate pool of knowledge in a particular field**. If restricted to fairly narrow fields, the number of patents and publications can provide useful measures. But due to the differences among disciplines, it is questionable how much information this method would yield across a broader spectrum of fields.

EFFECTIVENESS OF THE KNOWLEDGE BASE[2]

How effectively is the knowledge base used, i.e., to what extent is it converted into economic performance?

[2]This section draws heavily on Carlsson, Jacobsson, Holmén and Rickne (1999).

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

When a particular knowledge field constitutes the *level of analysis*, the objective of the exercise tends to be to unravel the process of generation and diffusion. Whereas the performance of this process may be assessed via patent and bibliometric studies, it is quite difficult to measure the economic performance associated with the use of that knowledge. This is so for three reasons. First, only rarely is a particular knowledge field economically useful on its own; it needs complementary technologies in order to form various types of products. Second, any given knowledge field may enter a broad range of industries but play only a minor role in each of them. Third, the role of a given knowledge field may change rapidly over time but in an uneven fashion in different industries.

Measuring the performance of a system is a great deal easier if the level of analysis is a product, industry or group of industries. In our early work on factory automation (Carlsson 1995), the main performance indicator was the extent of *diffusion* of factory automation in Sweden, as compared to other countries, using conventional diffusion analysis. Keeping the product, or industry, as the unit of analysis we could, in later studies (Carlsson 1997), use patents to calculate the *revealed technological comparative advantage* as an indicator of the *generation* of knowledge and conventional performance indicators of the *use* of technology, such as market shares and exports. Hence, satisfactory ways of measuring the performance in terms of the generation, diffusion and use of technology, in the sense of an artifact, are available.

For an *immature* system, the measurement problems are greater. No single indicator is likely to be sufficient to capture performance and, therefore, several measures have to be combined to give an assessment of the performance in what may be called the fluid phase (Utterback, 1994) of a system. In particular, indicators of performance in terms of both generation of knowledge and diffusion and use of that knowledge are important to incorporate. Below, we sketch some possible measurements that may be combined for an effective evaluation (see table 2). None of these measurements alone can describe the performance, but combined they may give a more complete assessment of how well an emerging system is performing.

The indicators are drawn from Rickne (1999) who studied firms active in a set of young and science-based technologies, namely biomaterials which is a sub-set of the biomedical field.

Table 2 Examples of performance measures for an emerging technological system

Indicators of generation of knowledge	Indicator of the diffusion of knowledge	Indicators of the use of knowledge
1. Number of patents 2. Number of engineers or scientists 3. Mobility of professionals 4. Technological diversity, e.g. number of technological fields	1. Timing /The stage of development. 2. Regulatory acceptance 3. Number of partners/ Number of distribution licenses 4.	1. Employment 2. Sales 3. Growth 4. 4. Financial assets

Source: Rickne (1999)

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

As the technology is science-based, product development requires a great deal of time. Developing products for a medical device or pharmaceutical market requires clinical trials, and regulatory issues further delay market entrance, i.e., the *diffusion* process from the lab to the market is lengthy. Thus, an evaluation of the 'closeness' to market exploitation was deemed to be appropriate. Rickne employed two different market-related measures of performance. First, she assessed whether or not the product had received regulatory acceptance by government authorities. Second, as the majority of the companies within this section of the biomedical industry need an agreement with a partner in order to have access to distribution channels, the number of partners was used as an indicator of closeness to market exploitation.

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

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

CONCLUDING REMARKS

(Yet to be written.)

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