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The Influence of Technological Capabilities on Knowledge Network Component of Innovation Systems: Evidence from Advanced Materials

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Abstract

This paper is concerned with the dynamics of innovation systems (IS) in emerging economies. It investigates how one core element of an IS, namely its network of knowledge links changes over time and how that change may be influenced by change in the deepening technological capabilities of firms. It contributes to the IS literature by addressing this question for the first time by: (i) examining change over a relatively long period of time (1967 to 2001), (ii) using knowledge link as tool for analysis that firms used particularly in their technology projects to introduce new product/process technology and (iii) implementing quantitative analyses on data collected through detailed, face-to-face interviews in advanced materials firms. We found evidence that it is particularly the deepening technological capabilities of firms that drive the emergence and evolution of the knowledge network component of IS.

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Abstract. This paper is concerned with the dynamics of innovation systems (IS) in emerging economies. It investigates how one core element of an IS – its network of knowledge links – changes over time and how that change may be influenced by change in the deepening technological capabilities of firms. It contributes to the IS literature by addressing this question for the first time by: (i) examining change over a relatively long period of time (1967 to 2001), (ii) using 'knowledge link' as tool for analysis that firms used particularly in their technology projects to introduce new product/process technology and (iii) implementing quantitative analyses on data collected through detailed, face-to-face interviews in advanced materials firms. We found evidence that it is particularly firms' deepening technological capabilities that drive the emergence and evolution of the knowledge network component of IS.

Key words. Technological capabilities, sectoral innovation systems, knowledge networks, advanced materials, developing countries.

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1. Introduction

This paper deals with the dynamics of innovation systems (IS) in manufacturing industry in emerging economies, with particular reference to the experience of advance materials sector in Turkey. It investigates how two core elements of a sectoral innovation system, the network of knowledge links and the technological capabilities of firms, change over time. More importantly, it examines the co-evolution of these two system elements – albeit centered only on the one-way influence of changes in firm capabilities on changes in the characteristics of knowledge networks.

It is widely argued that innovation-related knowledge networks are weakly articulated in developing and emerging economies (Bell and Albu, 1999; Giuliani and Bell, 2005; Dantas and Bell, 2009; Figueiredo, 2010b). This is usually seen as involving the low incidence, or even absence, of two kinds of innovation-related knowledge link: (i) between domestic firms and local organizations like universities and R&D institutes, and (ii) between domestic firms themselves. Also, knowledge links between domestic firms and actors outside the domestic economy are often not considered to be elements of the 'national' innovation system. If they are considered at all, they are typically treated as being in competition with intra-country linkages and acting as substitutes for these linkages (Lundvall, 1992; Nelson, 1993). However such cross-border links are also important features of the knowledge network of a 'sectoral' IS and there are important questions to ask about the roles in the overall system that are played by such links and about how the characteristics of such links change over time as the system evolves. Such questions are rarely addressed. Indeed, questions have rarely been addressed about how overall structure of links in the knowledge network change as an element in the long-term development of IS in today's emerging economies. We know even less about the factors that influence change in those network structures.

It is also widely recognized that at early stages of industrialization, technological capabilities of firms in developing countries are typically weak and that an important part of the overall industrialization process involves firms making long-term transformation of these capabilities as they move from imitation to innovation (Kim, 1997, 1997a, 1998, 1999; Cohen and Levinthal, 1990; Lall, 1987, 1992). Previous studies also provide important insights on, for example, micro-level learning processes that contribute to the accumulation and transformation of technological capabilities, the time paths that may be involved, and even about some of the factors that influence the rate of transformation (Dantas and Bell, 2009; Figueiredo, 2010a, 2010b) . However, we know very little about the interaction between those paths of firm-level capability accumulation and the evolution of innovation system characteristics, in particular the structure of knowledge networks. To the extent that this interaction is considered, the IS literature views it as one that runs *from* network characteristics *to* firm capabilities – stronger and denser network links of various kinds are seen as contributing to the accumulation of stronger technological capabilities in firms. Such a view contributes to policy perspectives that focus on measures to try and strengthen linkages and network structures as a central element in efforts to strengthen IS. However, in this paper we argue that it is important to examine that relationship the other way round – i.e. to consider whether and how changes in firm-level technological capabilities influence change in the structure of knowledge networks.

Therefore, this paper aims to answer the research question "*How do the increments in firm-level technological capabilities influence the emergence and the elements of a system of innovation?"* by staying within the boundaries of the 'firm'. We explore this relationship in the context of the advanced materials sector in Turkey, covering two segments: the 'science-based' segment using sophisticated and novel processes and producing complex products and the 'mature technology' segment using relatively mature techniques to produce conventional products. We show how the structure of the knowledge networks and the strength of firms' technological capabilities evolved over about thirty years, and then we examine how the development of capabilities shaped the changing network structure within the IS. In undertaking this exploration we contribute to understanding the dynamics of IS development in the process of industrialization in ways that have been rare or absent hitherto: we illuminate changes in system characteristics over a much longer period than has been typically attempted, we examine an aspect of the co-evolution of different system characteristics, and we address the second of those issues by implementing quantitative analysis that has emerged from an intensive fieldwork that gathered information on knowledge links within sectoral innovation system.

The paper is organized as follows. Section 2 focuses on the theoretical background and investigates the role of technological capabilities and knowledge networks as related to the IS. Section 3 provides background information about the materials sector in Turkey. Section 4 describes the methodology. Section 5 presents the descriptive and the econometric results. Finally, section 6 forms the conclusions.

2. Background Literature and Conceptual Framework

Literature on emerging markets/ industrialising countries has a consensus on the weak technological capabilities of firms at early stages of industrialization and emphasizes that, for the most part, acquisition of novel technologies from abroad serves as the basis for capability assimilation and accumulation (Lall, 1987; Contractor, 1998; Howells, 2000; Tsai and Wang, 2008). These capabilities evolve and strengthen over time as firms accumulate higher levels of such capabilities and as their absorptive capacity rises (Cohen and Levinthal, 1990). Thus, firms improve their "ability to make effective use of technological knowledge in efforts to assimilate, use, adapt and change existing technologies" (Kim 1997a: 86; Bell and Pavitt, 1993; 1995). To build up and strengthen such capabilities firms need a *prior knowledge base,* which could be identified by the strength of human resources and capital resources in the firm and they also need an *intensity of commitment* to carry on building up such capabilities, which could be identified by continuously investing in R&D and design activities, conducting preparatory searches prior to knowledge acquisition and labor mobility (Kim, 1998; Cohen and Levinthal, 1990).

On the other hand, the early development of IS ideas centered on questions about cross-sectional differences in broad modes of innovation. That comparative interest lay behind the early macro-level analyses of Freeman (1988) and Nelson (1993); and it underpinned the sector-level studies of Pavitt (1984) and those that contributed to Lundvall (1992), as well as the later elaborations on those perspectives as 'technological systems' (Carlsson and Stankiewicz, 1995) and 'sectoral systems' (Breschi and Malerba, 1997). In the context of the advanced economies that emphasis on cross-sectional comparison has persisted but, within that, increasing emphasis has been given to the dynamics of IS – both the co-evolution of their component elements (e.g. Malerba, 2004), and the emergence of their functional characteristics (e.g. Bergek et al. 2008) and activities (Edquist, 2005; Edquist and Chaminade, 2006). There has been even less examination of IS dynamics in developing and emerging economies, despite the inherent interest and importance of understanding how systems emerge and develop in those contexts. This has been partly because of the limited availability, but also limited relevance, of time-series data commonly used in the more advanced economies (primarily R&D expenditure and patents). Combined with the difficulties of generating alternative types of quantifiable data, this has led research to rely heavily on more qualitative information, commonly leading to descriptive studies and very limited treatment of change over time. In that context, particularly the concept of national innovation system (NIS) has been a major tool for policy makers both in the developed and developing parts of the world. The emphasis in NIS is mainly on within-border interactions and their investigation. Indeed, the initial phase of acquiring knowledge and technology has largely been via cross-border linkages in the late-industrialized world Lundvall (2007). Some of the case studies in Malerba and Mani (2009) mark a step forward in attempting to examine aspects of the dynamics of sectoral systems in this context without confining the interactions into national boundaries. Malerba (2004) incorporates firm-level learning and technological capability accumulation in the firm into the analysis of the system. The accessibility of knowledge – both internal to the sector (mainly via inter-firm interactions) and external to the sector (mainly via universities or research laboratories), technological opportunities either created in the universities or in R&D by firms, as well as the cumulativeness of knowledge via learning processes, firm-specific capabilities and feedback from the market are substantial aspects of the knowledge acquisition process in Malerba's sectoral IS. Malerba and Mani (2009) strikingly show that learning and the formation of capabilities in domestic firms were found to be among the common factors across sectors.

Therefore, despite firm-level technological capabilities and their paths of accumulation have been widely discussed in the literature (e.g. Lall, 1992; Bell and Pavitt, 1993; Ariffin and Bell, 1999; Dutrenit, 2000; D'Este, 2002; Iammarino, Padilla-Perez and Von Tunzelmann, 2008; Figueiredo, 2010a, 2010b) empirically it somehow remained largely unconnected to the IS concept, perhaps except Malerba's (2004) work. In the extant IS literature , the relationship between technological capabilities and system characteristics has always been constructed from the system characteristics to technological capabilities indicating that a good habitat of IS would be reflected on favorable conditions for the firms, the industries and the country and thus leading to improving capabilities at all levels (Nelson, 1993; Lundvall, 1992). Having been very instructive and constructive for emerging economies for policy development in IS, this construct has an institutional perspective (see Figure 1 dashed arrow). On the other hand, purely at the firm level the relationship from technological capabilities to system characteristics, as employed in this paper, has been overlooked. This perspective argues that the deepening technological capabilities in the firms may ease these firms' access to more valuable knowledge networks and therefore intensify their network structure within IS (see Figure 1, solid arrow). Therefore, even though we are completely aware that the causality[1] will be acting in both directions indicating a co-evolution of these two concepts (as shown by both arrows in Fig.1), for the stated arguments below in this paper we will focus on the causality from capabilities to knowledge networks component of IS.

Figure 1 about here

R&D and patent statistics have received much of the emphasis in the above-mentioned studies merely because of their availability and reliability. One can discuss the drawbacks of solely relying on these statistics in capturing the effects of very complex qualitative dimensions of empirical studies of IS in the developing country context. Similarly, Freeman (1997: 29-30) remains critical about a large volume of studies by OECD on countries' technological indicators, which are mainly driven by R&D measures as the source of innovation. Standardized by the Frascati Manual (OECD, 1963), this approach dominated the research first in developed and then the developing countries. Even though R&D is a strong indicator of innovation in the firms, there are certainly other important factors influencing technical change – i.e. "education, training, production engineering, design, quality control, etc." (Freeman, 1997: 30). In connection with that, some studies particularly focus on the *knowledge network* component of IS, in search for whether the increasing level of technological capabilities could also be a reason for emerging and co-evolving knowledge networks in a system. They stem from previous work on knowledge flows among the actors of a system, user-producer interactions leading to product innovations (Hakansson, 1987, 1989; von Hippel, 1988; Andersen and Lundvall, 1988; Johanson and Mattson, 1988; Fagerberg, 1992). Hakansson's (1987, 1989) work highlights the importance of industrial networks especially between the suppliers, customers and producers. Even though mostly excluded the non-firm organizations and the role of internal technological activities in the firms, it was useful in initially attracting attention to inter-firm relationships in product innovations and provided valuable examples of how different types of actors interacted with each other – i.e. vertical and horizontal cooperation between firms. Hagedoorn and Schakenraad (1990) analyze different modes of cooperation of firms, changing from joint venture to licensing agreements, specifically for

[1] Widely applied Granger causality test assumes that the information relevant to the prediction of variables is contained solely in the time series data on these variables (Gujarati, 1995). Even though recently there are considerations on the application of Granger test on panel data frameworks (see Hurlin and Venet, 2001; 2004 and Hurlin 2005) these do not yet provide solutions within packaged software such as STATA, SPSS, etc. Moreover, this is an issue by breadth and depth that deserves serious tackling, probably on its own in a whole paper.

knowledge exchange. They emphasize the role of strong interactive links for knowledge exchange and argue that strong, productive, competitive industries and firms with strong technological capabilities tend to interact more with the outside world. In other words, in the literature, the 'common sense' has always been existent that the developing country firms needed to hold at least some level of existing capabilities in order to start 'valuable' international networking in the way that they would benefit from and improve their capabilities further (in comparison to very simple arm's length relations) (Freeman and Hagedoorn, 1994). The question then was how improving their technological capabilities influenced their ability for further networking.

As the literature moved towards differentiating knowledge networks from other kinds of networks (e.g., production and trade networks), the former were better clarified in an attempt to understand more about change-generating technological activities in the firms that evolve over time (Bell and Pavitt, 1993; 1995). Knowledge networks component of IS, their characteristics, the role of actors and interactions in these networks have become the focus in Gelsing (1992), Bell and Albu (1999), Giuliani and Bell (2005), Dantas and Bell (2009) and Figueiredo (2010b). Gelsing (1992:117) clearly distinguishes between trade networks and knowledge networks: The former focus "mainly on linkages between users and producers of traded goods and services" and the latter focus "on the flow of information and exchange of knowledge irrespective of its connection to the flow of goods". Along with the understanding that "technological change is not simply something firms choose and buy-in from outside, but it is rooted in a specific set of change-generating resources or capabilities which are located *within* the structure of firms" (Bell and Albu, 1999: 1718), the firm-driven nature of knowledge networks came under investigation in the literature. By then, many authors have stressed that successful firms are the ones that can combine and balance the knowledge they acquired from the external sources with their internal activities and knowledge generation in the firms (Cohen and Levinthal, 1990; Bell, 1997; Kim, 1997; Howells, 2000). Bell and Albu (1999) examine knowledge networks and state that a knowledge system encompasses major differences from a production system. While the former are identified with "stocks and flows of knowledge" (p.1722) between firms and their partners which underlie change-generating technological activities in the firms, the latter remains confined to routine activities related to the production of goods. They explicitly state "knowledge flows can occur into the firms from outside the system, between firms and other institutions within the system or indeed internally within firms themselves" (p.1723). In their study of a Chilean wine cluster, Giuliani and Bell (2005: 64) challenged the views in the literature that clusters provide good habitats for technological learning for firms irrespective of their level of knowledge base since the expectations were that the knowledge diffusion within the cluster allowed all cluster firms to get hold of knowledge available.

Thus, the knowledge network approach provides a useful tool by focusing on knowledge flows and allows for feasible empirical analyses with certain measurable parameters. This paper makes use of the knowledge network approach as an empirical tool, but does not undermine the cumulative role of studies conducted within the IS approach that clarified the vital ingredients of a system in its narrow definition, that is 'actors' and 'interactions'. However, having said a lot about the networks, actors and the institutional structure, very little of IS literature informs about how these elements change over time in relation to improvements in technological capabilities of the firm, particularly in emerging economies. Therefore, further research is needed to trace and highlight the changes over time in the narrowly defined characteristics of the IS and the much-neglected factors, such as firm-level technological capabilities, that drive these changes.

This paper attempts to examine such changes in structural features of networks of knowledge links to acquire new product and process technology over a thirty-five year period. It also examines how these changes were associated with the progressive deepening of the technological capabilities of the knowledge-acquiring firms from simple technology-operating capabilities, to new, original product and process development capabilities. Therefore, this paper aims to answer its research question within the below conceptual framework (Fig. 1). We deal with two selected aspects of the knowledge network of a sectoral IS, namely the 'density of links' in the system and the 'actors/sources' (firm vs. institute) in the system. Moreover, we examine actors/sources by taking into account their geograhical 'origin of link' (domestic vs. foreign).. The density of the links helps elaborating the changing structure of knowledge network over time, while the influence of incremental improvements in the firm's technological capabilities on knowledge links will be examined with regard to the actors/sources in the system according to their geographical origin of link.

3. Advanced Materials Sector

The advanced materials sector involves manufacturing of metals, ceramics, composites and polymers.[2] Starting from the 1970s, there has been an accelerating increase in the study and applications of advanced materials in the universities and industry in the developed parts of the world. These materials started replacing the traditional materials (e.g. iron, standard steel, copper, aluminum, etc.) in mostly high technology applications. Today, it has evolved into a science-based, knowledge intensive and high value-added sector, which delivers products for almost all other industries, from automotive to aerospace, telecommunications, energy, electronics, chemicals, defense, biomedical, machinery and textiles. Thus, the sector distinguishes itself as a sector, which can connect its own dynamism to other related manufacturing sectors through both vertical and horizontal links, and therefore get integrated in a wide range/variety of knowledge networks. This arises mainly due to the increasing cost-effectiveness and high-performance of advanced materials in comparison to traditional materials.

Based on the kind of product, the materials production can be broadly classified into two[3]: (i) Products identified by their structural[4] properties (e.g. powder metallurgy parts and fiberglass, ceramic refractory) and by the use of medium technology processes in production (e.g. wet/dry/hydraulic pressing, sintering, casting, etc.) ; and by their application in medium technology sectors, such as ferrous and non-ferrous metal parts for the automotive sector, iron and steel, standard glass and ceramic sectors, standard electronics, etc., and (ii) High technology products (e.g. optical fiber, fiber-reinforced composites, technical ceramics such as piezoelectric, oxygen sensors, ultra-hard thin-film ceramic coatings), identified by their functional[5] properties and by the use of higher technology processes (e.g. Injection moulding, resin transfer moulding,

[2] It is not possible to classify these products directly within industrial classifications such as ISIC, NACE, etc. They are rather dispersed in different divisions and groups, creating a major obstacle for obtaining any kind of data on these products. A basic guideline on where these products may fit into ISIC Rev.4 may appear as below:
Small metal powder metallurgy parts in Division 25 - Manufacture of fabricated metal products, except machinery and equipment under Class: 2591 - Forging, pressing, stamping and roll-forming of metal; powder metallurgy.
Fibreglass, ceramic refractories and technical ceramics in Division 23 - Manufacture of other non-metallic mineral products under Class: 2310 - Manufacture of glass and glass products; Class 2391 - Manufacture of refractory products and Class: 2393 - Manufacture of other porcelain and ceramic products, electrical insulators and insulating fittings of ceramics, ceramic and ferrite magnets, ceramic laboratory, chemical and industrial products (i.e. ultra-hard thin-film ceramic coatings). Fibreoptic cables in Division 27 - Manufacture of electrical equipment under Class 2731 - Manufacture of fibre optic cables.

[3] This classification will also prepare the basis for studying and comparing two different segments; namely, mature technology firms and science-based technology firms, in the Turkish advanced materials sector.

[4] Structural properties of a material refer to mechanical properties such as high strength, high-temperature strength, wear resistance and lightweight.

[5] Functional properties of an advanced material refer to the physical, chemical and biological functions possessed by the material. These may relate to high thermal conductivity or insulation, high electrical conductivity or resistance, high chemical stability, piezoelectricity, corrosion resistance, biocompatibility, etc.

ion implantation, chemical vapour deposition, magnetron sputtering, plasma enhanced vapour deposition, etc.) and use of R&D; and by their application in high technology sectors such as telecommunications, complicated electronics, defense and aircraft, etc.

Turkish Statistical Institute does not maintain production and consumption statistics of the above-discussed traditional and advanced materials. Even if it were possible to have these statistics, they would not be reliable, since the companies usually do not reveal the real figures for production because of tax matters in Turkey. Thus, we provide import/ export values of some of the materials in Appendix Table A1.[6] Turkey showed a steady change in its industrial specialisation patterns from resource-based to traditional products (from the beginning of the 1960s to the end of the 1980s) and then to medium technology products (from the 1980s to mid 2000s). The exports of structural materials have increased considerably from 2000 to 2005 due to favourable conditions in the automotive industry, which is the main buyer for iron and copper based powder metal parts. More than half of the exports of functional materials are of fibre optics. Technical ceramics account for less than half. And among the technical ceramics, exported items fall into medium technology category products such as fuse insulators and aluminium oxide parts. Despite that, the materials sector in Turkey is more import-oriented than export-oriented. Demand for functional materials is mostly covered by imports and its domestic production meets internal demand with negligible rates of export.

4. Methodology

(a) Data Collection and Sample Formation

The sample formation procedure involved several steps: (i) selection of firms of which the knowledge links would be enquired, (ii) face-to-face questionnaire implementation at selected firms, (iii) data processing and formation of the dataset based on knowledge link being the unit of analysis.

The firms were selected using several means of information channels: Consultations with TTGV[7], TUBITAK-TIDEB and other key experts at research institutes in Turkey. One-page pilot questionnaire was implemented, enquiring about firm activities and process technologies. 19 firms out of 75 responded. The results from this survey highlighted that the sample could be grouped into two as (i) 10 science-based firms

[6] TURKSTAT gathers these statistics (GTIP – Customs Tariff and Statistics Position) according to 'Customs Entry-Exit Declarations' by Customs Offices throughout Turkey. Then, they are organized on the basis of the 'Harmonized System Nomenclature' of the EU and according to 'statistical positions' arranged in the 8-digit code of the 'Customs Entry Instructions'.

[7] TTGV (Turkish Technology Development Foundation) is a World Bank sponsored NGO in Turkey.

producing high-complexity novel products with high-technology processes[8], and (ii) 9 traditional firms producing relatively conventional products with mature technology processes.[9] Also, science-based technology firms were distinguished from the others, with percentages of researchers and engineers above 20%. On the other hand, to put the comparison on an acceptable basis and to be able to interpret the collected data, commonalities between them are concerned only with private and small and medium scale firms from the materials sector. All firms have employees under 500 as it fits the definition of an SME from the employment point of view. On the basis described above, the comparison here resembles very much Kim et al.'s (1989: 34-37) small firms with high capability (science-based technology firms) and small firms with low capability (mature technology firms), which in turn are expected to exhibit dissimilar patterns of technological capability accumulation and linkage characteristics.

The data were collected through face-to-face semi-structured interviews[10] in June 2001 with key informants such as managers, chief engineers of production and especially R&D units in the firms. The questionnaire focused on obtaining (i) *Information on firm interactions* that elaborate knowledge links of the firm with the domestic and foreign communities differentiated also as other firms, institutes and intra-firm sources; and (ii) *Link-specific information on technological capabilities* of the firm that draws on technological capability accumulation, details about the main process technology currently in use and other process technologies and secondary technologies that have been transferred or developed previously. It had the advantage of allowing for focused questioning in a formal way and providing some flexibility to adapt to the wide variety of circumstances in the firms. Interviewees responded very well to this interview format. They were willing to share their information. The minimum time for an interview with each individual was four hours. They were always complemented by a visit to production sites accompanied by an engineer of the firm. These moments were invaluable opportunities to confirm some of the information given by the main interviewee or to double-check some important information gathered. In addition to interviewing

[8] For instance, the use of the physical or chemical vapour deposition technique for production of ultra thin film ceramic coatings on metal or glass surfaces; production of optical fibre; production of small intricate technical functional ceramic parts by injection moulding methods for use in electronics, biomedical, steel industries; production of polymer matrix composites for use in defence and aerospace industries, etc.

[9] For instance, a hydraulic press for production of metal powder composite parts produced especially for the automotive and manufacturing cutting tool industries; production of fibreglass, etc.

[10] Face-to-face interviewing method provided us with creation of a unique dataset. No existing data sources provided information about the changes over time in key features of the innovation systems within which these firms were embedded in this industry in Turkey. Among other sources of data, the archives of firms could be used provided that they existed; however none actually existed, given the family-owned SME nature of firms in the sample.

representatives from companies, interviews were completed with representatives of key knowledge production institutions in the materials field, such as metallurgical engineering and materials science departments of universities, materials departments of national research centers, and directors of the technology development centers where some firms in the sample are located. Moreover, in cases of research projects conducted with universities or research institutes, these auxiliary interviews were sources of valuable information regarding the details of specific projects and the actual role of the firm in those projects.

In processing the data, to start with, the 'technology project' concept was brought into the analysis as an intermediate tool to dig into the knowledge links of firms associated with each project. This also allowed to efficiently organize the raw qualitative data obtained from the interviews. Technology project is defined as any type of firm activity that the firm undertakes for acquiring technology, as well as the specific production and research activities with knowledge flows. These can be activities ranging from arm's length activities such as simple transfer of machinery or know-how transfer to collaborative activities such as technical assistance and cooperation or strategic alliances. Therefore, within each firm, the acquired information was listed with respect to each of a sequence of 'technology projects' through the lifetime of the firm. This provided a total of 289 technology projects spreading over 35 years, with the earliest establishment of a firm in 1967.[11] Further on, within each technology project we have enquired about the knowledge links. A 'knowledge link' is defined as kind of interaction between the firm and any one of the actors/sources in the system of innovation (including intra-firm sources) through which primarily knowledge is transferred to the firm by any means of technology transfer within a particular technology project. The domestic or foreign partner may be another firm or an institute in the form of a knowledge supplier. Knowledge links are attributes of technology projects; and there may be more than one knowledge link attached to a technology

[11] The total number of technology projects is, indeed, a sample from the population of technology projects that had actually taken place throughout the lifetime of a firm, due to a possibility of a recall issue about some of the initial projects. The earlier the implementation of a technology project, the more likely it is for the informant not to recall a project that actually might have taken place. However, it is important to stress that, as explained earlier, the firms, in this study, are predominantly family-run enterprises with unbroken institutional memories greatly reduces this problem. Vast majority of the managers in the sample firms have been managing the firm since its establishment. In a few older firms, the son or daughter of the owner took over the managerial position, but in such cases the first generation manager was met and interviewed as well. Additionally, frequent opportunities to meet chief engineers of production and especially R&D units, who in some cases worked in the firm since its establishment, were always taken. As a result, in order to overcome a possibility of bias, the technology projects needs to be handled with extreme care when dealing with the frequency of technology projects.

project. For instance, production of a new product in the firm might be conducted in a way that involved knowledge links with (i) a university department, (ii) a customer firm, and along with (iii) contributions from the firm's own R&D unit. In that particular case, there would be three knowledge links associated with the-one technology project. Therefore, within each technology project, information was sought about what technology was acquired and how through each of several 'knowledge links' involving different sources. There were between one and five actively performed links per project, and the total of 289 technology projects provided a total of 408 observations of knowledge links (which formed the primary database). In proposing the 'knowledge link' concept, we had one objective in mind. It would increase the number of observations and indeed allow for the data to be configured in the way that they could be used in econometric analyses. It is useful in finding and highlighting the details about each single interaction of firms and studying them in quantitative analyses, which would not be possible if the 'firm' were to be used as the unit of analysis.

(b) Database

We have used two databases throughout the analysis.

Primary Database: A categorical[12] *primary set of data* (each cell in the dataset representing one knowledge link, in total 408 links). This panel dataset is used in descriptive analyses to examine the basic structure of the IS and changes in the system over time (see Section 5a).

Database-2: A dataset derived from the primary dataset (for the econometric analyses). The primary dataset with 408 observations is transformed into a new dataset with 209 observations by re-arranging (adding up) the number of links for each variable of the primary dataset for three-year intervals during the total period of 1967 to 2001. By this way, a pooled dataset (formed by count variables[13]) is obtained for the linkages of 19 firms. Database-2 is especially arranged to yield the occurrences of outcomes in a given period of time, so that one can assess the influence of accumulated capabilities during the previous period on the firm interactions during the next period. That would comply with the implementation of negative

[12] Categorical data may derive from either or both of observations made of qualitative data, where the observations are summarized as counts or cross tabulations, or of quantitative data, where observations might be directly observed counts of events happening or they might be counts of values that occur within given intervals. Often, purely categorical data are first summarized in the form of a cross-tabulation (see section 5a).
[13] Count variables indicate how many times something has happened in a given time period (Long and Freese, 2006:349).

binomial regression models especially designed for 'count variables' (Long and Freese, 2006). Moreover, using the occurrence of events in a given time period would be statistically more objective approach, rather than running binary logit or multinomial logit regression on the primary categorical database. The latter is designed to match each link with each capability increment and is not suitable for tracing the effect of lagged capability increments on the links, simply because some links may occur simultaneously within the same technology project. We remind again that the ultimate aim of this paper is to search for the effect of technological capabilities on firms' interactions with the implicit assumption that capability increments in a previous time period may affect interactions in the later period (see Section 5b).

(c*) Variable Definitions, Measures and Models*

The variables used in the analyses are defined as follows.

Dependent variables. There are five dependent variables to be used in the models. They refer to the knowledge links of firms by geographical origin and type of actor, i.e. *domestic firm links, domestic institute links, foreign firm links, foreign institute links and intra-firm links*. By this way, we are able to differentiate between origin of link, i.e. domestic v. foreign as well as system characteristics of firm interactions, i.e. firm-firm, firm-university or research institute interactions[14] and intra-firm[15] sources. Other firms interacted with are observed as rival firms operating in the same field, process technology supplier and raw material supplier firms from domestic or foreign environment.

Independent variables. *Technological capability accumulation.* Inspired by Lall's (1992) categorization of technological capability levels, technological capability accumulation is operationalised by

[14] In this study, 'institutions' will be regarded as 'organisations'. These are 'formal structures with an explicit purpose' or what are normally called organisations as described in Nelson and Rosenberg (1993) and not 'things that pattern behaviour' like norms, rules and laws as described in Lundvall (1992). Therefore, organisations in the 'institution' concept in this research are narrowed down to represent the universities, national research institutes and private research institutes that pursue R&D activities.

[15] During the interviews with the firms, it was observed that there are considerable amount of activities undertaken in the firms using their own in-house sources. They were initiated within the firm, usually with the initiative of the manager or an engineer in the firm. These activities might solely rely on the firm's engineer(s) or sometimes be further supported by other external partners at different points of a technology project. They are called 'intra-firm sources' in this research. In most discussion in the systems of innovation literature, such activities would not be included in the analysis of the concept. Interactions between the actors of the system and outsourcing knowledge would be the main concern. Yet, neglecting organisational and individual learning in the firm (Edquist, 2001: 3) and in-house efforts at the firm level within the context of technological learning (Kim, 1997: 91) has been one of the major weaknesses of IS approach. In-house efforts are vital for internal digestion of the knowledge acquired from external sources. Because such activities contribute immensely to capability accumulation, which in turn is expected to influence networking in the innovation system, they are deliberately classified as the third category of the type of source. However, they are examined separately from firm and institute linkages.

‘Increment in *operational* capability for process or none’, ‘Increment in product or process *improvement* capability’ and ‘Increment in product or process *development* capability’, as three independent variables to be used in the analysis.[16] Similar forms of technological capability leveling approach have been successfully used in previous research examining developing countries (see for example, Ariffin and Bell, 1999; Iammarino, Padilla-Perez and Von Tunzelmann, 2008; Figueiredo, 2010a, 2010b). This approach allowed us to implement a comparative analysis based on levels of incremental technological capabilities in the next stage of econometric analyses.

While constructing increment in capability variables, asking firms directly about the level of capability they achieved through their links would not be a reliable approach. Instead, links were assessed for their outcomes, in the form of increments to their existing level of capability related to each knowledge link in the technology project. Each link added some more knowledge to the prior knowledge of the firm compared to the previous one. In the interview questionnaire, initially each technology project that took place in the firm (e.g. technology development or technology acquisition and its extensions or renewals) was explored. Then, information was sought about the incremental technological capability that was acquired with respect to the knowledge link of the firm. To derive the outcome from the technology project and the associated knowledge links the firms were explicitly asked “*What was the main outcome from the technology project? What was the outcome from knowledge link?*” Firms revealed the outcomes from their links, whether it was operation of a technology, improvement of a technology or a new product. These were identified as increments to the current capability of the firm, and the outcomes were listed. Thus, this proxy is purposefully used to comment on and decide upon the increment of technological capability achieved as a consequence of interaction between the firm and an institution or another firm. Observations related to these outcomes are classified depending on Lall’s (1992) categorization of technological capabilities to derive the independent variables to be used throughout this research (see Appendix Table A2). Initial and low levels of increments in capability concentrating on the basic use of processes and products are put into the category of operational capability for process technology. Increments of intermediate level capabilities are categorized under improvements in processes and products. For instance, these consist of incremental capabilities to undertake

[16] Lall (1992: 167) provides a sophisticated classification for basic, intermediate and advanced technological capabilities. Each level of capability is further categorized according to their relations with pre-investment, project execution, process engineering, product engineering and linkages within the economy. However, only capabilities related to process and product engineering in Lall’s classification is considered within the focused scope of this paper.

medium-technology process development, and modification of an acquired process by contributions from the firm's engineers enrolled in postgraduate programs of a domestic university or recruitment of skilled labor. Kim (1997a: 341) also notes that Korean science-based firms, with the assistance of domestic universities or smaller foreign firms, can build sufficient capability to crack technology through advanced reverse-engineering, though mature technology firms with insufficient capability could not progress further in this case. Finally, incremental capabilities towards higher technology process and product design, modification and development are regarded as evidence of development of process or product technology. In addition to the categories elaborated here, a fourth observation for the case of 'no incremental capability acquired' emerged during the course of interviews. Such observations amount to 7% of the total observations in the primary dataset. This category is combined with 'increment in operational capability' category for ease of use in the econometric analyses.

Control variables. *Firm type.* As explained in section 3, the classification of the products and process technologies used in the advanced material sector allows us to differentiate between the firm types as science-based versus mature-technology firms.

Time period. Since one important aim of this research is to trace changes in a system of innovation over time (i.e. the deepening technological capabilities and the changing nature of knowledge links in the context of this research), we introduced three time periods into the analysis. While doing that, we considered allocation of knowledge links between time periods as representative of a dynamic analysis and explanatory as possible, and took into account the historical events in Turkish economy. As of 24 January 1980, the Turkish government went through radical changes in its whole economic policy and switched from import-substitution to export-orientation development policies. Changes also included deregulation of money and capital markets, and so on. This radical change influenced the governance of the economy from that date onwards. Therefore, allowing period I from 1967 to 1981 draws a line between two completely different economic policies applied in Turkey and captures this radical shift in the economy. Period I is identified with the industrialization strategies towards import substitution. Impacts of the application of export-orientation policies in the industry after 1980 were felt gradually during the following years. It is the rather lagged influence of the passage to a market economy in 1980 that resulted in an increasing number of activities in firms, especially from 1995. Another factor was the introduction of the Internet in the country from the mid

90s. Many firms in the private sector linked up with the Internet. This radical innovation caused firms instantly to be aware of recent changes and innovations in their field and adjust accordingly. Consequently, the three periods emerged as (i) 1967-1981, (ii) 1982-1996 and (iii) 1997-2001.

This study regresses the dependent variables (knowledge links with foreign firms, domestic firms, foreign institutes, domestic institutes and intra-firm sources) on independent variables (increment in capability, INCCAP) and controls (firm type and time period). To operationalize these relationships we make use of the below main equations:

(1) Foreign firm link = $\alpha_0 + \alpha_1 INCCAPoperational_t$ *or* $INCCAPimprovement_t$ *or* $INCCAPdevelopment_t + \alpha_2 INCCAPoperational_{t-1}$ *or* $INCCAPimprovement_{t-1}$ *or* $INCCAPdevelopment_{t-1} + \alpha_3 Dfirm_{science} + \alpha_4 Dperiod_{1997-2001} + u$

(2) Domestic firm link = $\beta_0 + \beta_1 INCCAPoperational_t$ *or* $INCCAPimprovement_t$ *or* $INCCAPdevelopment_t + \beta_2 INCCAPoperational_{t-1}$ *or* $INCCAPimprovement_{t-1}$ *or* $INCCAPdevelopment_{t-1} + \beta_3\ Dfirm_{science} + \beta_4\ Dperiod_{1997-2001} + u$

(3) Foreign institute link = $\gamma_0 + \gamma_1 INCCAPoperational_t$ *or* $INCCAPimprovement_t$ *or* $INCCAPdevelopment_t + \gamma_2 INCCAPoperational_{t-1}$ *or* $INCCAPimprovement_{t-1}$ *or* $INCCAPdevelopment_{t-1} + \gamma_3\ Dfirm_{science} + \gamma_4\ Dperiod_{1997-2001} + u$

(4) Domestic institute link = $\varphi_0 + \varphi_1 INCCAPoperational_t$ *or* $INCCAPimprovement_t$ *or* $INCCAPdevelopment_t + \varphi_2 INCCAPoperational_{t-1}$ *or* $INCCAPimprovement_{t-1}$ *or* $INCCAPdevelopment_{t-1} + \varphi_3\ Dfirm_{science} + \varphi_4 Dperiod_{1997-2001} + u$

(5) Intra-firm link = $\delta_0 + \delta_1 INCCAPoperational_t$ *or* $INCCAPimprovement_t$ *or* $INCCAPdevelopment_t + \delta_2 INCCAPoperational_{t-1}$ *or* $INCCAPimprovement_{t-1}$ *or* $INCCAPdevelopment_{t-1} + \delta_3 Dfirm_{science} + \delta_4 Dperiod_{1997-2001} + u$

We used negative binomial regression analyses,[17] designed especially for count outcome dependent variables in STATA (STATA, 2009) on database-2.

[17] We prefer negative binomial regression model to Poisson regression model, since the latter rarely fits due to overdispersion (Long and Freese, 2006:372). We also tested for overdispersion and found significant evidence of overdispersion (chibar2 (α) significance <0.01) in our models (see Table 4), which further supports the preference of negative binomial regression models over Poisson regression models.

Table 1 about here

Table 1 presents the descriptive statistics for the variables that we used in the econometric analyses. It is noticed that on average foreign linking outweighs domestic linking and firm links outweigh links with institutes. The partial correlation tests reveal that the capability variables are significantly correlated with each other. To prevent further problems, which may arise with multicollinearity in the regressions, dependent variables are regressed on each level of capability increment separately. Also, because the capability increments in one period may influence the structure of the system in a later period, the variables are constructed to represent time-lagged capability increments in the models.

5. Results

(a) *Descriptive Results*

The analysis of firms' technological capabilities focuses on the increment of capabilities that they have acquired through each knowledge link. The "All links (count)" row in Table 2 shows the rising frequency of links during the three periods.[18] The table also shows that over time for firms in the sector, proportion of links with acquisition of development capabilities of a product or process increased from nil during 1967-1981 to more than one-third of all links in 1997-2001, and the proportion of links with increments in operational capabilities was more than halved from 1967-1981 to 1997-2001. This pattern was more emphasized in the science-based segment of the sector, particularly for acquisition of development capabilities in the final period.

Table 2 about here

Along with firms' levels of technological capability accumulation, the sources of knowledge networks were also changing over time in the materials sector in Turkey. Table 3 suggests that from 1967 to 2001, the proportions of inter-firm links were decreasing and those of institute links were increasing during the subsequent periods, whereas intra-firm sources remained largely the same for the science-based segment of

[18] This is likely to reflect an element of recall error, especially for the early period. However, as explained earlier detailed aspects of the research method were explicitly designed to avoid this, and we believe any inaccuracy is very limited.

the sector. Thus, the structure of the IS was shifting from inter-firm linkages to firm– institute linkages over time. The firms have been less dependent on especially foreign technology supplier firms and more in collaboration with the domestic knowledge holders such as universities and research institutes.

Regarding intra-firm sources, however, the two segments of the sector behaved differently. This pattern was more emphasized in the science-based segment of the sector with foreign firm links decreasing from 72.7% in the first period to 41.9% in the final period and domestic institute linking increasing from nil to 24% in the third period. Use of intra-firm sources presented a more stable pattern in the science-based technology firms from the first period to the third period (18.2%, 15.6% and 20.9%), but a fluctuating pattern in mature technology firms (18.8%, 25% and 7.2%). Only, during the final period, the science-based segment of the sector was likely to use intra-firm sources considerably more than the mature technology firms. The former was becoming more self-sufficient by investing in its more stabilized in-house development efforts over the years. These findings suggest that for the science-based technology firms at least, the network structure was becoming internalized over time.

Table 3 about here

Systems are usually defined by the volume and characteristics of the linkages that bind them together (Archibugi et al., 1999: 531). The volume of interactions is important in a system in order to characterize whether it is a vibrant or inert system. Table 3 also shows that the proportion of knowledge linkages was increasing and the IS was getting more vibrant over time. For example, during the first period, the firms' proportion of all linkages was only between 5 and 8% but by the third period, that proportion was more than 58%. The density of links (frequency per firm per year) increased almost five-fold in the third period compared to the first period. Even though the science-based segment had slight advantages over the mature segment of the sector in terms of the proportions of projects and links; by means of the density of links the mature segment of the sector managed to catch-up with the science-based firms in the final period (2.47 and 2.62).

Thus, it seems that especially the last five years analyzed can be identified with emerging major changes in the two different segments of the Turkish advanced materials sector. Foreign links were being replaced by domestic links and inter-firm links were being replaced by institute links as the firms' acquired additional technological capabilities were deepening over time. In the light of these findings, we discuss in the next section the relationship between the two core elements of the advanced materials sector sectoral IS, particularly the influence of deepening firm-level technological capabilities on the characteristics and the structure of knowledge networks.

(b) Econometric Results

Tables 4 and 5 present the results of regressions and the average marginal effects through Model 1a to Model 5c respectively. The overall fit of each model is statistically significant at the 1% level as indicated by LR chi^2 significance values. The Pseudo R-square[19] values are also within the acceptable range, most of them highly satisfactory, for each model. We found positive and statistically significant results for increments in technological capabilities being strongly influential on the network characteristics of firms. The coefficients for increments in operational capability, improvement capability and development capability at time t are all positive and highly significant and the marginal effects related to these coefficients are all positive.

Tables 4 and 5 about here

Firstly, the results suggest that a unit increase in any level of capability increment results in increasing links with the sources of knowledge. Yet, as the level of additional capability increases firms are likely to build fewer knowledge links with foreign firms and foreign institutes (marginal effects for foreign firms 0.57>0.39>0.21 in Models 1a, 1b, 1c and for foreign institutes 0.11>0.08>0.03 in Models 3a, 3b, 3c in order for operational, improvement and development capabilities). As their acquisition of additional capability levels increase from operational to improvement of product or process, firms are likely build more knowledge links with domestic firms and domestic institutes (0.06<0.09 in Models 2a, 2b and 0.08<0.18 in Models 4a, 4b, respectively). For the former, the interaction would mostly take place between the firm and a foreign technology supplier firm, whereby the firm would just import the process technology and at most receive training to operate the machine. For the latter, these interactions mostly involve modification or replication of existing process technologies within a joint project with a domestic research institute aiming at

[19] Pseudo R square is a measure bounded in between 0 and 1 and according to Tabachnick and Fidell (2007: 460) "values in the 0.2 to 0.4 range considered highly satisfactory (Henscher and Johnson 1981)".

the production of a new product. At this stage, the firm is already confidently able to operate the machines and conduct troubleshooting.

However, as the firms' acquisition of additional capability levels increase from improvement to development of product or process, firms are likely build fewer links with domestic firms and domestic institutes (0.09>0.03 in Models 2b, 2c and 0.18>0.06 in Models 4b, 4c, respectively). This suggests that advanced capability levels of product or process development, indeed hinder domestic linking. It is probably because domestic organizations cannot provide the advanced level of knowledge that such firms require. Or in some other cases largely related to science-based segment of the sector, it may be that the confidentiality of knowledge in highly complex product or process production could be important for the firm and that deters the firm from expanding its networks. This particular issue has been raised during the interviews especially by young science-based ventures that used for instance the sophisticated process technologies of ultra-hard thin-film ceramic coatings, modified and developed either their own process or products so that they wanted to keep the know-how strictly to themselves. In the developing country context this concern is understandable, since patents and IPR measures do not seem to work as effectively as they do in the developed parts of the world. Rojec and Jaklic (2001) also observed similar patterns in the car components industry of Slovenia that relationships between suppliers and buyers tend to diminish as the type of product moves from high complexity to very high complexity. Therefore, the findings of this research suggest that increasing level of technological capabilities in the firms lead to increasing number of interactions, but something certainly happens to cause firms to abstain from interacting further when technological capabilities reach more advanced levels at which firms start to produce complex and high technology products or deal with complex processes. The reasons for this may be surprisingly different in the developing and developed countries as well as in the large and small firms. This finding certainly calls for further research at different levels.

Secondly, the regression results suggest that as the additional level of capability increases, firms are less likely to use their own sources (the marginal effects are 0.30>0.21>0.10 in Models 5a, 5b, 5c in the order for operational, improvement and development capabilities). Yet, compared to their external domestic links, they are still more likely to use their own sources (marginal effects for intra-firm sources and domestic institute links are 0.30>0.08 in Models 4a, 5a, 021>0.18 in Models 4b, 5b and 0.10>0.06 in Models 4c, 5c for operational, improvement and development capabilities, respectively). The firm type effect for science-based technology firms appears to be not statistically significant in Models 5a to 5c however; the previous cross-tabulation analyses shed some light on this issue. For instance, Table 3 suggests that over time, science-based firms' use of intra-firm sources presented a more stable pattern compared to a fluctuating pattern in mature technology firms. The former presented a more self-sufficient pattern and during the final period, they were likely to use intra-firm sources considerably more than the mature technology firms due to their higher level of knowledge base and intensity of effort. The latter, however, were likely to replace the use of their own sources, wherever not sufficient, with domestic institute links during the final period when they considerably gained product or process development capabilities even for low and medium level technologies. These findings are striking in the way they tell that firms were less likely to use their own sources as their capability levels increased, but it seems that this was due to different reasons in both kinds of firms. Whereas the science-based segment of the sector appeared to be self-sufficient to make the most use of their intra-firm sources over time, the mature segment of the sector had less sufficiency in the third period and with their capability levels increasing they turned to domestic institutes.

Lastly, it must be noted that, even though it is observed that the firms were increasingly opting to collaborate with domestic partners, foreign partners, and especially foreign firms – despite their share in total linkages consistently decreasing over time – remained as one of the main technology suppliers. Being in a developing country, this sector is indeed largely dependent on foreign novel technologies. Also, given the fact that the vast majority of the knowledge links that were associated with domestic links were those that yielded capability increments in technology improvement, this suggests that the sector in general is at the stage of imitation. Therefore, it is quite reasonable for the firms to try to network with both the domestic and the foreign worlds.

The lagged capability variables are not statistically significant in majority of the models. Only the lagged operational capability variable had a strong influence on foreign links in Model 1a. These findings actually state that firms' acquisition (3 years or earlier) of higher-level capabilities (i.e. for improvement and development) does not influence their networking. But previously acquired operational capabilities would be strongly influential on foreign links. Since, this is a sector dependent on foreign technologies it is probable that the firms' earlier acquaintances with foreign technology suppliers would be very important in keeping these relationships going. Whether the supplier provided satisfactory technical help in the aftermath of technology acquisition, which usually contributes an increment in its operational capabilities to the firm, would be taken into consideration by the firm in its later preferences for technology acquisition. In majority of models, period from 1997 to 2001 was found to be statistically significant and influential on firms' networking characteristics compared with the period from 1967 to 1996. Moreover this was especially related to improvement and development capabilities rather than operational capabilities. This finding strongly points to the emergence of an IS within the last five years regarding this particular sector.

6. Conclusion

(a) Summary and Implications

This paper explored how the core elements of a sectoral IS changed over time – the network of knowledge links and the technological capabilities of firms; as well as examining the much-neglected relationship of these two system elements – albeit centered on only the one-way influence of changes in firm capabilities on changes in the characteristics of knowledge networks of the IS.

First, we showed that firm-level technological capabilities were deepening over time, with increasing proportions of firm linkages, especially in the science-based segment, demonstrating the emergence of capabilities for incremental improvement and for more original product/process development. Second, we showed that the overall 'density' of the knowledge network of the materials sector innovation system increased over time – the frequency of knowledge links per firm per year increased five-fold between 1967-1981 and 1997-2001. Within this, the network became increasingly 'internalized'– a rising proportion of knowledge links was with sources inside the domestic economy. This finding is in accordance with Nelson's (1993, 2004) proposition, among others, that especially indigenous universities and public laboratories play a vital role in the system. Regarding the role of firms themselves as sources of the new technology they used, moved in different directions in the two segments of the sector, and by the end of the whole period the science based firms were about three times as likely as firms in the mature segment to use their own development efforts to generate some of their technology. This can be explained by better labour and factor endowments, i.e. foreign educated managers, higher rate of researchers, active R&D and design activities, etc. in the science-based technology firms (Griliches, 1986; Cohen and Levinthal, 1990; Kim 1997a, 1999;

Zahra and Covin, 1994; Zahra and George, 2002). In the developing country context, we have found to some extent evidence for Kogut's (2000) claim as to industries characterized by science-based technologies tend toward rules that promote cooperation between research centers and firms, but that was mainly when firms' capabilities were at the level of product or process technology improvement, not development.

A striking finding, therefore, is that the relationship between firms and domestic agents was not continuous: as firms reached the higher levels of product/process development capability, they reduced the frequency of links with domestic sources – perhaps because domestic organizations could not provide the advanced levels of knowledge that firms require for more original innovative activities. The science-based technology firms increasingly turning to their own sources particularly by the final period also explain the knowledge insufficiency of domestic institutes. This seems as a disadvantage for an effective IS in the long term in a developing country. Relevant STP implementations should address the problem and take the necessary measures to strengthen the technological capabilities at the firm level instead of focusing purely on firm R&D oriented policies in Turkey, where 90% of the firms do not conduct any R&D activity at all. However, it is more difficult task to do than to say. While there are exceptions, not many developing countries have been able to perform well in this area.

It can be concluded that this is an IS making much use of firms beyond its national borders and institutes within the national borders. Links with the former are mostly based on importation of process technologies which is necessary as a start to build further capabilities on, while the links with the latter are based on in-depth knowledge flow and knowledge generation in a bilateral environment. In firm-institute linkages there is a full potential of process and product technology imitation and generation that is also supported by firms' own sources, especially in the case of science-based segment of the sector. However, this is at a very embryonic stage, and whether an effective IS emerges or not depends on the success of these kinds of linkages.

Overall, these findings from the Turkish advanced materials sector suggest that it is firms, and in particular firms' own technological capabilities, that drive the evolution of the knowledge network of the IS. This means, particularly when indigenous universities remain mostly ineffective for advanced technology firms, firms opt for their own sources or knowledge sources abroad, indicating that they seek knowledge wherever it may be. Yet, the mature segment of the sector turns to universities for knowledge flow, well received for their level of activities.

(b) Limitations and Future Research

Some limitations and directions for future research are worth mentioning. First, previous research uses measures of human capital to capture absorptive capacity – i.e. the number of scientists, engineers, and trained engineering graduates, and personnel skill levels (see Keller, 1996; Liu and White, 1997; Glass and Saggi, 1998). Since absorptive capacity is positively related to the acquisition and use of external knowledge (Cohen and Levinthal, 1990; Kim, 1997a, 1999; Zahra and George, 2002), the relationship between human capital measures and external technology acquisition on firm's capabilities should also be explored. Likewise, Walker, Kogut and Shan (1997) state that not only organizational behaviour but also social capital determines the formation of inter-firm networks or it may even be the cooperative decisions of firms arising out of generative rules in specific competitive markets (Kogut, 2000).Second, such a firm-driven perspective also needs to be complemented by the fact that it is also via knowledge links that firms acquire much of the inputs to augment their capabilities. A more extended analysis could therefore show a pattern of interactive co-evolution between firms' capabilities and the structure of the system's knowledge networks. Such an interactive co-evolution between firms' capabilities and knowledge networks would probably be mediated by aspects of the firm's strategy in managing its technology acquisition projects, however that would probably differ in both kinds of firms, so that they contribute effectively to deepening technological capabilities. Such interesting issues are worthy of further exploration in the future.

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Appendix

Table A1. Import/ export values of structural and functional materials in Turkey for selected years,USD mil

			1997		2000		2005	
Material group		**End Product**	imports	exports	imports	exports	imports	exports
Structural materials	Metal	Iron and copper based powder metal parts for automotive ind.	344.4	77.4	257.9	102.6	587.7	367.3
		Hard metals-metal composites for metal manufacturing ind.	36.2	2.3	43.1	2.2	43.9	39.3
		electrolysis	0.5	0.1	3.6	0.05	2.9	0.2
	Glass	fibreglass	21.9	34.5	25.5	37.2	66.0	81.4
	Ceramics	refractories	24.6	11.2	13.8	8.7	38.2	32.8
	Structural materials total		427.7	125.4	343.9	150.7	738.8	521.0
Functional materials	Glass	fibreoptics	7.8	12.7	4.1	23.6	4.2	23.0
	Technical ceramics	Electro porcelain parts: Low & medium tension insulators	3.8	0.3	3.0	0.2	3.1	1.3
		Steatite parts: Fuse insulators	6.3	2.3	7.5	1.3	10.8	4.3
		Aluminium oxide parts: Seal rings, thermostat parts, thermocouple tubes.	37.3	2.3	29.3	1.4	57.7	11.9
		Ceramic electric condensors	8.6	0.1	17.4	0.1	11.0	0.1
		Cordierite and mullite-cordierite parts: honeycomb strainers for metal casting.	9.8	0.03	15.2	0.1	23.1	0.1
		Ceramic ferrites	8.6	0.1	6.4	0.3	12.9	0.2
		Piezoelectrics	6.9	0.01	1.9	0.1	3.7	0.0
		Thin film ceramic coatings on metal and glass surfaces (only for titanium oxide)	8.5	0.1	6.7	0.02	7.4	0.1
		Ceramic-metal composites	0.9	0.02	0.1	0.00		
		Technical ceramics total	81.2	5.1	80.6	3.5	122.4	18.0
	Functional materials total		89.0	17.8	84.8	27.2	126.6	41.0

Source: TURKSTAT (1997, 2000, 2005).

Table A2. The construction of independent variables: *Increment in Capability*, as inspired from Lall (1992) and corresponding technical examples.

Lall's (1992) categorization of technological capabilities related to process and product engineering only	**Adaptation of observations from this research to Lall's categorization as increments in capabilities with respect to the previous knowledge link**	**Selected specific technical examples**
BASIC CAPABILITIES (Simple-Routine-Experience based) a) related to process engineering: Debugging, balancing, quality control preventive maintenance, assimilation of process technology b) related to product engineering: Assimilation of product design, minor adaptation to market needs	**Increment in capabilities for operation of process or product technology** a) related to process engineering: Transfer of machinery, equipment and know-how with respect to low-tech, medium-tech and state-of-the-art processes, process operation, enhanced process operation, process troubleshooting, etc. b) related to product engineering: Knowledge acquisition of new products and their uses, product introduction to foreign markets	**Powder Metallurgy:** Acquisition and operation of wet pressing, dry pressing, cold isostatic pressing, hot isostatic pressing, hydraulic press, injection moulding machine, sintering furnace, peripheral technologies (i.e. surface finish, drying furnace, etc.) and quality control machines. **Optical fibre:** Acquisition and operation of extrusion and wire drawing machine, acquisition and operation of fibre optic drawing tower. Training received from a Japanese firm on fibre optic production machines. **Composites:** Acquisition and operation of composite production technologies (i.e. filament winding machine, pultrusion, Resin Transfer Moulding (RTM) machine) and peripheral technologies (i.e. blender, melting furnace, bushing, binder application). Production of "launch tube" made of fibre reinforced composite material using filament winding technique in European Stinger Project. **Technical ceramics:** Acquisition of machines and know-how and operation of flame spray, plasma spray coating, cathodic arc plasma vapour deposition (PVD), ion implantation, chemical vapour deposition (CVD) techniques and diamond-like carbon (DLC) coating s.
INTERMEDIATE CAPABILITIES (Adaptive-Duplicative-Search based) a) related to process engineering: Equipment stretching, process adaptation and cost saving, licensing new technology b) related to product engineering: Product quality improvement, licensing and assimilating new imported product technology	**Increment in capabilities for improvement of process or product technology** a) related to process engineering: Additional competence to undertake low-tech process development, modification of acquired process by contribution from the firm's engineers enrolled in postgraduate programs of domestic university or from recruitment of skilled labour, capability to use complex quality control machine and to interpret test results b) related to product engineering: Acquisition of know-how only with respect to state-of-the-art product, quality control equipment, competence to create improved product	**Powder Metallurgy:** Own process development of dry pressing from learning-by-using of wet pressing. Further modification of mechanical dry pressing machines. Further modification of hydraulic press. Further modification of injection moulding machine. Own process development of heating furnace, sintering furnace. **Composites:** Own development of labour intensive hand lay up technology for composite production. Establishment of electromechanical assembly line for gyroactivator production. Research on bending behaviour of filament-wound tubes. Sponsoring a doctoral thesis on "flaw control in RTM". In-house replication of radio frequency dryer by reverse engineering. **Technical ceramics:** Sponsoring doctoral researchers (own engineers) for "prevention of cracks occurring in ultra-thin film ceramic coatings". Further modification of cathodic arc PVD by reverse engineering. Training received on operation of Scanning Electron Microscope (SEM). Sales of license to firms from Uzbekistan, Iran and Saudi Arabia for fuse systems.
ADVANCED CAPABILITIES (Innovative-Risky-Research based) a) related to process engineering: In-house process innovation, basic research b) related to product engineering: In-house product innovation, basic research	**Increment in capabilities for development of process or product technology** c) related to process engineering: Additional competence to undertake own high-tech process technology development, electronic equipment design for own process technology, software design for own process technology, design of own process technology d) related to product engineering: Additional competence to create a new product (for the firm or domestic market)	**Powder Metallurgy:** Own process development of injection moulding machine by reverse engineering. Own production of W-based alloy products by injection moulding. **Optical fibre:** Own design and replication of fibre optic drawing tower by reverse engineering. Development of fibre optic preform and process technologies using semiconductor deposition techniques MCVD-chemical vapour deposition and OVD- outside vapour deposition, Production of submarine F/O cable box and development of techniques for installation of cables in submarines, Development and application of radiation enduring optical fibres, Production of multimode fibre optic preform and multimode fibre optics, Development of pure silica corn for Swiss CERN (within a research project), Development of boron dopped preform for a Japanese firm producing dispersion maintaining fibres for direction determining military aircrafts.

	Composites: Optimum design of high pressure filament-wound composite tubes. Production of polymeric matrix composites for airframes of short range-high mach number missiles. Development of RTM for aerospace structural components. Composite pressure vessel design and prototype production by filament winding. Development of pre-fragmented composite war head and bomb structure. Development of light anti-personnel rocket system. Development of a new product with polypropylen reinforcement by filament winding. Production of prepregs (carbon-impregnated composites) for light transport aircrafts. Production of submarine battery box by RTM. Design and development of all composite UAV (Unmanned Aerial Vehicle). Design and development of all composite target drones. **Technical ceramics:** Production of catalytic convertor and heat distributor ceramics. Production of complex shaped ceramic dies of BC, WC and Co materials and mechanical strengthening of die surfaces by Plasma Enhanced Vapour Deposition (PVD). Development of PVD magnetron sputtering technique. Development of ultra-thin film ceramic coatings (i.e. TiN, ZrN, TiZrN, TNO using PVD magnetron sputtering; ZrHfN, ZrHfCN, TiCN coatings using cathodic arc PVD) . Development and application of ultra-thin film ceramic coatings on glass substrates, medical protheses. Development of thick non-stick coating to be used in textile industry. Development and production of ceramic ferrites. Development and production of piezoelectrics. Development and production of low calcium refractories. Development and production zirconia oxygen sensor to be used in steel industry. Own development of of cathodic arc PVD by reverse engineering,

Figure 1. Conceptual framework: Key concepts and variables

ΔTechnological Capability — Knowledge Networks in the System of Innovation

*Increment in capability

* Origin of link in the system (domestic v. foreign)
*Type of source in the system (firm v. institute)
*Density of links

Table 1. Descriptive statistics (N=209)

	Min	Max	Mean	S.D.	6	7	8	9	10	11	12
1.intra-firm link	0	6	0.33	0.909							
2.Foreign firm link	0	15	0.99	2.033							
3.Foreign institute link	0	4	0.11	.496							
4.Domestic firm link	0	3	0.18	0.512							
5.Domestic institute link	0	8	0.33	0.977							
6.INCCAPoperational	0	11	1.02	1.864	1						
7.INCCAPimprovement	0	8	0.45	1.069	0.552**						
8.INCCAPdevelopment	0	10	0.47	1.584	0.494**	0.318**					
9.INCCAPop (lag)					0.172**	0.200**	0.389**				
10.INCCAPimp (lag)					0.163**	0.317**	0.359**	0.498**			
11.INCCAPdev (lag)					0.177**	0.250**	0.235**	0.409**	0.307**		
12. Dperiod 1997-2001					0.541**	0.487**	0.582**	0.495**	0.510**	0.325**	
13. Dfirmsciencebased					-0.06	0.014	0.081	-0.033	0.026	0.117	0.000

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

Table 2. Distribution of links by increment in capability, period and firm type categories (%) (N=408)

	Science-based technology firms			Mature technology firms		
INCREMENT IN CAPABILITY	**1967-81**	**1982-96**	**1997- 01**	**1967-81**	**1982-96**	**1997- 01**
Operational or none	100.0	61.0	33.3	93.8	73.4	47.4
Improvement	0.0	27.3	23.3	6.3	26.6	22.5
Development	0.0	11.7	43.4	0.0	0.0	29.7
All Links (%)	100	100	100	100	100	100
All Links (count total 408)	11	77	129	16	64	111
Firms (count)	2	9	10	5	9	9

Source: Author's interviews.

Table 3. Distribution of knowledge links by actor, period and firm type categories (%) (N=408)

	Science-based technology firms			Mature technology firms		
KNOWLEDGE LINKS	**1967-81**	**1982-96**	**1997- 01**	**1967-81**	**1982-96**	**1997- 01**
Firm links	81.8	64.9	47.3	81.3	60.9	66.7
Foreign firm links	72.7	57.1	41.9	68.8	48.4	55.0
Domestic firm links	9.1	7.8	5.4	12.5	12.5	11.7
Institute links	0.0	19.5	31.8	0.0	14.1	26.1
Foreign institute links	0.0	7.8	7.8	0.0	3.1	5.4
Domestic institute links	0.0	11.7	24.0	0.0	10.9	20.7
Intra-firm links	18.2	15.6	20.9	18.8	25.0	7.2
DENSITY OF LINKS						
Technology Projects (%)	4.7	33.8	61.5	10.7	33.6	55.7
Knowledge Links (%)	5.1	35.5	59.4	8.4	33.5	58.1
Density of links (frequency per firm per year)	0.73	0.84	2.62	0.39	0.59	2.47
Pearson Chi-square Tests	(asymp. sig. 2-sided)			(asymp. sig. 2-sided)		
FIRMTYPE v. KNOWLEDGE LINK	0.073*					
PERIOD v. KNOWLEDGE LINK	0.022**			0.002***		

*Significant at 10% level, **Significant at 5% level, ***Significant at 1% level.
Source: Author's interviews.

Table 4. Results of negative binomial regressions.

Independent variables	Dependent variables														
	Foreign firm link			**Domestic institute link**			**Foreign firm link**			**Foreign institute link**			**Intra-firm link**		
	Model 1a	**Model 1b**	**Model 1c**	**Model 2a**	**Model 2b**	**Model 2c**	**Model 3a**	**Model 3b**	**Model 3c**	**Model 4a**	**Model 4b**	**Model 4c**	**Model 5a**	**Model 5b**	**Model 5c**
	B (s.e.)	**B (s.e.)**	**B (s.e.)**	**B (s.e.)**	**B (s.e.)**	**B (s.e.)**	**B (s.e.)**	**B (s.e.)**	**B (s.e.)**	**B (s.e.)**	**B (s.e.)**	**B (s.e.)**	**B (s.e.)**	**B (s.e.)**	**B (s.e.)**
INCCAPoperational	0.45*** (0.06)			0.36*** (0.07)			0.73*** (0.17)			0.22*** (0.08)			0.47*** (0.12)		
INCCAPoperatio-lag	0.22*** (0.06)			-0.03 (0.14)			0.52*** (0.18)			0.11 (0.09)			0.11 (0.13)		
INCCAPimprovement		0.38*** (0.11)			0.50*** (0.09)			0.64*** (0.14)			0.48*** (0.09)			0.53*** (0.18)	
INCCAPimprove-lag		-0.03 (0.12)			-0.09 (0.16)			0.06 (0.16)			0.02 (0.12)			-0.13 (0.18)	
INCCAPdevelopment			0.20*** (0.07)			0.18*** (0.06)			0.26* (0.15)			0.17*** (0.06)			0.26** (0.11)
INCCAPdevelop-lag			0.07 (0.08)			-0.24 (0.20)			-0.06 (0.21)			0.11 (0.08)			-0.03 (0.16)
DPeriod1997-2001	0.42 (0.26)	1.61*** (0.29)	1.46*** (0.32)	0.42 (0.56)	1.30*** (0.39)	1.43*** (0.41)	-0.46 (0.84)	2.05*** (0.66)	1.59** (0.77)	2.26*** (0.44)	2.54*** (0.40)	2.35*** (0.40)	0.83 (0.52)	1.53*** (0.45)	1.19** (0.48)
Dfirmsciencebased	0.21 (0.20)	-0.13 (0.24)	-0.11 (0.24)	-0.27 (0.36)	-0.84** (0.37)	-0.60 (0.35)	1.91** (0.78)	0.27 (0.58)	0.76 (0.62)	0.36 (0.35)	0.10 (0.33)	-0.03 (0.33)	0.21 (0.39)	-0.10 (0.38)	-0.31 (0.39)
Constant	-1.57*** (0.20)	-0.92*** (0.19)	-0.82*** (0.19)	-2.60*** (0.34)	-2.38*** (0.31)	-2.17*** (0.29)	-6.05*** (1.09)	-4.33*** (0.68)	-3.69*** (0.60)	-3.02*** (0.38)	-3.07*** (0.39)	-2.58*** (0.33)	-2.50*** (0.36)	-2.06*** (0.30)	-1.73*** (0.28)
α	0.286	1.145	1.207	3..3e-06	0.050	9.2e-06	1.537	1.289	3.383	0.959	0.615	0.591	2.076	2.140	2.076
Chibar2 (α) (01) (p)	6.54 (0.005)	43.34 (0.000)	41.99 (0.000)	0.0e+00 (0.500)	0.02 (0.448)	0.0e+00 (0.500)	6.88 (0.004)	4.34 (0.019)	11.30 (0.000)	12.93 (0.000)	10.06 (0.001)	6.52 (0.005)	31.86 (0.000)	29.05 (0.000)	25.65 (0.000)
Log likelihood	-193.88	-231.76	-234.20	-73.15	-79.08	-86.48	-44.96	-48.57	-58.13	-106.05	-97.59	-106.66	-120.23	-125.23	-128.13
LR chi2 (4) (p)	141.72 (0.0000)	65.96 (0.0000)	61.08 (0.0000)	58.18 (0.0000)	46.33 (0.0000)	31.52 (0.0000)	46.03 (0.0000)	38.82 (0.0000)	19.70 (0.0006)	68.76 (0.0000)	85.68 (0.0000)	67.54 (0.0000)	45.26 (0.0000)	35.24 (0.0000)	29.46 (0.0000)
Pseudo R2	0.27	0.12	0.12	0.28	0.23	0.15	0.34	0.29	0.15	0.24	0.31	0.24	0.16	0.12	0.10

N=209. *Statistically significant at 10% level. **Statistically significant at 5% level. ***Statistically significant at 1% level.

Table 5. Marginal effects at mean.

Independent Variables	Dependent Variables														
	Foreign firm link			Domestic firm link			Foreign institute link			Domestic institute link			Intrafirm source		
	Model 1a	Model 1b	Model 1c	Model 2a	Model 2b	Model 2c	Model 3a	Model 3b	Model 3c	Model 4a	Model 4b	Model 4c	Model 5a	Model 5b	Model 5c
INCCAPoperational	0.565			0.064			0.112			0.080			0.301		
INCCAPoperatio-lag	0.272			-0.006			0.079			0.039			0.072		
INCCAPimprovement		0.387			0.090			0.082			0.179			0.214	
INCCAPimprove-lag		-0.034			-0.017			0.008			0.007			-0.054	
INCCAPdevelopment			0.209			0.032			0.033			0.057			0.097
INCCAPdevelop-lag			0.075			-0.043			-0.007			0.037			-0.011
DPeriod1997-2001	0.522	1.651	1.519	0.739	0.230	0.253	-0.071	0.264	0.201	0.830	0.943	0.807	0.528	0.622	0.439
Dfirmsciencebased	0.258	-0.137	-0.119	-0.047	-0.149	-0.106	0.293	0.035	0.096	0.131	0.038	-0.010	0.014	-0.043	-0.114