Making knowledge visible: Using expert yellow pages to map capabilities in professional services firms

Paola Criscuolo^{a,*}, Ammon Salter^{a,b}, Tony Sheehan^{c,1}

^a Tanaka Business School, Imperial College London, South Kensington Campus, London SW7 2AZ, UK

^b Advanced Institute of Management Research, UK

^c Arup, 13 Fitzroy Street, London W1T 4BQ, UK

Received 14 February 2006; received in revised form 8 August 2007; accepted 10 August 2007

Abstract

Professional services firms survive by exploiting the skills and knowledge of their employees to deliver a range of projects for clients. As a result of working on these projects, an organization's capabilities evolve in unpredictable and often divergent ways. In order to help their staff conduct these projects, services firms have invested heavily in knowledge management systems. To date, few attempts have been made to use the information contained in these knowledge management systems to understand the nature and evolution of capabilities in professional services firms. Using the expert yellow pages of Arup, one of the world's leading engineering consultancies, we develop a new approach based on co-word and proximity analysis to map the knowledge and skills of professional services firms. This approach provides a mechanism to allow such firms to better understand what they know and help them to deploy their skills in new and potentially lucrative ways.

© 2007 Elsevier B.V. All rights reserved.

Keywords: Knowledge; Capabilities; Knowledge management; Professional services firms

1. Introduction

Professional services firms rely on the skills and abilities of their staff to perform projects. As a result of working with many different clients the skills and capabilities of these firms continuously evolve in unpredictable and often divergent ways. Indeed, their projects can be regarded as experiments across different organizations in specific circumstances, which provide opportunities to develop and deploy new knowledge. In

order to enhance their project performance capabilities, professional services firms have invested heavily in knowledge management (KM) and KM systems, including substantial investments in systems involving project databases, expert yellow pages and electronic communities of practice. Although KM systems help a firm to share and create knowledge among its staff and with its clients, much of the information stored in these systems remains untapped by the firm's senior managers; these systems have become tools for supporting project delivery and problem solving, rather than enablers for decision-making in relation to firm strategy and organization. Despite the information that exists within their organizations, senior managers in professional services firms seem to not to know what is going on inside their firms—what skills and capabilities are being developed and deployed, and how these

* Corresponding author. Tel.: +44 20 7594 5958; fax: +44 20 7823 7685.

E-mail addresses: p.criscuolo@imperial.ac.uk (P. Criscuolo), a.salter@imperial.ac.uk (A. Salter), tony.sheehan@arup.com (T. Sheehan).

¹ Tel.: +44 20 7755 3240; fax: +44 20 7755 3669.

skills and capabilities are evolving through interaction with clients. Increasing competition in the professional services market means that firms must constantly strive to better exploit their knowledge assets, and communicate their value both internally and externally.

In essence, we lack the tools needed to map and understand the capabilities of these organizations (Miles, 2000; Miles, 2003; Drejer and Vinding, 2004). As is the case with other knowledge-intensive service firms, many of the traditional indicators of firm capabilities fail to capture the nature of the activities inside these organizations (Metcalfe et al., 2005). For example, few professional services firms use patents to protect their intellectual property and they are infrequent publishers of academic papers (Hipp and Grupp, 2005).

In order to better understand the nature of knowledge inside professional services firms, we worked with Arup, one of the world's leading engineering consultancy organizations; we analysed information contained in corporate expertise locator/yellow pages to develop a new approach for mapping the knowledge and skills of professional services firms. Our approach is based on a co-word and proximity analysis. It allows us to construct a bottom-up visualization of the knowledge and skills within the firm and to explore connections between different knowledge domains and individuals within the organization. This bottom-up visualization may enable professional services firms to gain a fuller understanding of what their employees know and how the knowledge embodied in different actors and groups within the firm is connected.

The paper is organized as follows. Section 2 explores the nature of the capabilities and project activity inside professional services organizations, focusing in particular on engineering consultancies. Section 3 outlines the study method and briefly describes Arup—its ways of working and its KM activities. Section 4 reports the results of the analysis. In Section 5 we discuss the findings in relation to the management of knowledge in professional services firms.

2. Theoretical and empirical background

Professional services firms are driven by the requirements of both new and existing clients, usually within a series of discrete projects (Maister, 1993). These projects often require hands-on interaction with clients and other organizations, leading to the co-production of new knowledge with clients and project partners (Turner and Keegan, 1999; Gann and Salter, 2000; Miles, 2000; Bettencourt et al., 2002; Dougherty, 2004). Professional services firms rely on their human capital, and

the knowledge that resides in their staff for the performance of specialized and unique projects (Grant, 1996; Hitt et al., 2001; Teece, 2003). The ability to perform projects is also based on organizational knowledge, and professional services firms have developed extensive operating routines to support their project work, including post-project reviews, team formation and assembly procedures, and KM systems (Hansen et al., 1999; Sarvary, 1999; Gann and Salter, 2000; Lowendhal et al., 2001; Suddaby and Greenwood, 2001). These operating routines allow such firms to offer a package of services that draw upon the experience and knowledge held within the firm (Ofek and Sarvary, 2001).

However, much of the knowledge that is held by professional service firms remains tacit, embedded in uncodified routines, and rooted in the firm's social context (Morris, 2001; Dougherty, 2004). In many professional services firms, particularly those focusing on innovation and creativity, it is the human capital assets that are invaluable and are the source of competitive advantage, because they are unique, rare, and difficult for other firms to imitate (Barney, 1991; Teece, 2002).

An important type of professional service organization is the engineering consultancy. Engineering consultancies offer a range of services to their clients, including feasibility studies, specialist technical inputs into projects, project management, etc. They are often involved in competitive bidding in the course of which they need to communicate their ability to deliver projects using the best knowledge and processes available. Engineering consultants tend to work in large, diverse project teams that span a variety of organizations. They work closely with upstream providers of architectural services and downstream contractors, developers, and suppliers of components and materials (Gann and Salter, 2000; Gann, 2000). Many engineering consultancy firms work primarily for the construction industry, a sector characterized by a particular pattern of industrial activity. In construction projects, specialists from independent firms collaborate within a project team, which is usually disbanded at the end of the project. In addition, project team members and clients differ from one project to another, increasing the risks of poor knowledge transfer and mistakes being repeated (Davies and Brady, 2000).

The project-based nature of their work, however, can make the activities of engineering consultancies appear highly episodic and ad hoc (Mintzberg and McHugh, 1985). Project work involves highly differentiated and customized demand; clients negotiate the design of products and services to meet their special requirements. Thus, the knowledge and skills needed to

perform some projects can be highly specific and localized. Other projects, however, may require more general knowledge that will be applicable across many different projects. The fundamental challenge for these consulting organizations is to translate project level learning into organizational capability (DeFillippi and Arthur, 1998; Turner and Keegan, 1999; Davies and Brady, 2000; Gann and Salter, 2000; Hobday, 2000; Davies and Brady, 2004; Davies and Hobday, 2005). The project-based nature of their activities means organizations working in the sector often struggle to learn from one project to another (Prencipe and Tell, 2001); a project's key lessons are rarely fed back to the other areas of the organization.

Engineering consultancies usually have a wide range of projects and skills operating at any one time. Arup, for example, performs up to 10,000 different projects every year, involving hundreds of different clients (Salter and Gann, 2003). Given this, it is difficult to grasp the range of activities undertaken by the firm, and the skills and knowledge created within the firm as a result of these projects. In addition, as in many professional services firms, the control of the central or senior management over the organization is limited, and ties between project groups are often weak (Hansen, 1999). Many project teams operate semi-autonomously and outside the boundaries of the firm (Maister, 1993; Gann and Salter, 1998).

In order to ameliorate some of these problems and to increase the effectiveness of their project performance and knowledge sharing between projects, engineering consultancies have invested considerable resources in KM and KM systems (Gault and Foray, 2003). Their approach to KM varies, with some organizations investing heavily in technology to capture knowledge through documentation and data and others introducing cultural change initiatives to encourage knowledge sharing within the organization (Nonaka and Takeuchi, 1995; O'Dell and Grayson, 1998; Hansen et al., 1999; Sarvary, 1999; Davenport and Prusak, 2000; Dixon, 2000; Cross et al., 2002; Argote et al., 2003). Much of the initial interest in KM was focused on knowledge structured within databases and document management systems (Zack, 1999). Whilst this is a critical component of an all-encompassing KM system, it soon became evident that such a structured approach, on its own, was unlikely to fully address the needs of complex engineering design (McDermott, 1999; Davenport and Prusak, 2000). Document and data management may be acceptable KM strategies for clearly defined process based sectors, but for more complex, design based activities, it is essential to understand the nature of knowledge in detail: to know what the organization knows.

Organizations seeking to 'know what they know' have adopted many different approaches to analysing the skills and capabilities of their employees. Some use advanced profiling tools to mine email and other activities, while others rely on formally validated systems that identify and sometimes rank individual skills (Davenport and Prusak, 2000). In Arup, a 'personal profile', in which individuals declare topics or areas of interest they feel confident about, is critical for identifying both expertise and areas for future development. These and similar tools also provide considerable information about the nature and evolution of a firm's skills. In particular, they highlight the new skills and capabilities that may be emerging in specialist groups, which may be operating largely independently within the firm, that are not widely known about by the organization.

To date, little attempt has been made by professional services firms to use this information for understanding the evolution of skills and capabilities inside their organizations. One reason for the lack of integration between the information held in KM systems and high level decision-making in professional services firms is that there are no means for aggregating or summarizing this information, in ways that are understandable and relevant for decision-makers; it tends to be used in projects on a day-to-day basis. Thus, such information has tended to be 'on the shelf', embedded in systems, and often ignored. In addition, in the past there was little need to understand skill combinations-engineering was characterized and its problems resolved by discrete disciplines. However, the increasing complexity of engineering design is demanding cross-disciplinary problem solving (Stankiewicz, 2000; Williams, 2002). The ability to understand critical skill combinations has become a strategic imperative for those organizations seeking to compete on value rather than cost. Some mechanism is required to extract from the information contained in KM systems, knowledge about the nature of the firms' skills and capabilities in order to enable managers to see what knowledge is being developed, combined and utilized by staff in performing projects. Such a mechanism may allow these firms to proactively harness potential complementarities between different areas of their organizations.

3. Method

3.1. The research setting

The firm of Arup, founded in 1946 by Sir Ove Arup, provides a range of design, engineering and associated services and currently has 71 offices across

50 countries, employing 6500 staff. Arup is recognized for its concentration of technical and design knowledge. It has been involved in some of the great building projects of the 20th century, including the Sydney Opera House and the Pompidou Centre.

Arup works on several thousand projects simultaneously, providing specialist advice to a diverse client base. The growth in the firm has been almost entirely self-generated. The company started as a structural engineering firm and with successive different projects its capabilities expanded into a number of areas. As the former Chairman of Arup, Bob Emmerson, stated: ‘Gifted people take us in unexpected directions’. The firm now comprises over 50 specialist groups, ranging from environmental consultancy to acoustics, and its services are continuously moving in new directions through a combination of new business opportunities and market demand.

Arup sees its advantage over competitors as its ability to combine a wide variety of specialist skills on projects. Reflecting the aims of its founder, it aspires to be a total problem solver, through the weaving together of diverse skills. Many of its competitors are small, specialized design services firms that have relatively few competencies and encompass a narrower range of engineering fields. Failure to share its knowledge and combine its skills effectively could leave Arup vulnerable in fast growing markets to cheaper, more agile competitors.

As previously mentioned, Arup’s growth has been accompanied by an increase in the number of specialist groups within the firm. New groups have developed within existing teams based on the ability of project leaders to recognize new market opportunities, to develop specialist service offerings, and to spin out new teams. Central management acknowledges the *de facto* independence of these teams. Senior managers in Arup have adopted the ‘let a thousand flowers bloom’ attitude to the management of these groups, and the company is highly decentralized. There is a feeling that attempts to impose central control on these groups might weaken their development, and the company’s senior management argues that groups should be left to get on with developing their own markets and skills. The management style adopted is similar to that found in many professional service firms employing highly creative people (McKenna and Maister, 2002).

KM at Arup has evolved as a response to this philosophy, based on a strategy initiated in 2000 and delivered and refined over succeeding years. The strategy focuses on people more than processes, with systems that target support for the decision-making process through a variety of voluntary actions rather than formal tools and

mandatory processes. This strategic selection is in keeping with an organization seeking to achieve innovation and creativity in its designs rather than standardization (Hansen et al., 1999).

Arup has always had a strong knowledge sharing culture, and a willingness among its employees to help one another. The imperative to preserve these behaviours strongly influenced the selection of technologies to support the KM strategy, with the development first of an expertise location system, followed by parallel systems to support the cultivation and delivery of communities of practice across the firm. Given the complexity of many of the projects undertaken by Arup, there is a frequent demand for new rather than standardized solutions. The solutions to client problems are rarely unique to one discipline or skills set, and generally demand the combination of different skills to create effective answers and add new value. This has had an influence on the firm’s approach to system development, with less emphasis on the skills that have been used in the past, and much more on finding new skills to cope with unpredictable and unexpected future problems.

3.2. Research approach

Our study involves working with our research partners to co-produce new knowledge (Tranfield and Starkey, 1998; Huff, 2000; Tranfield et al., 2004; Van Aken, 2004; Van Aken, 2005). To this end, we have taken problems from the real world of practice and attempted to apply the tools of social science to better understand the challenges, formulate new questions and resolve some of the problems. The research is premised on recognition of the mutual contributions of practitioners and academic researchers to research challenges and problem formulation. It is important in this type of work to find a common meaning and understanding across the practice and academic research worlds. In order to achieve this mutual understanding, we developed visual representations to create a space of meaning across different communities of practice.

The relationship between the research team and the partner organization is long established, and close. In the past 5 years, one member of the research team has conducted a number of different studies on the practices of Arup, including its use of simulations, sources of ideas for engineering design, and management of technology. Another research team member is directly responsible for KM in Arup. In conducting the present research, we worked with Arup to develop the initial idea, the method and the analysis. We were interested, in particular, in developing a method that would allow us to use

the information held by the firm to gain new insights into its evolving knowledge base and skills. By doing so, we hoped to influence thinking inside the firm about what areas of these capabilities were central to the business, and how new areas and skills could be harnessed to produce new value for its clients.

To further this goal, we examined individual skills descriptions in Arup's corporate yellow pages (expertise location system) and the data stored in the organization's human resource dataset, which include grade, tenure and office location for each individual. The skills descriptions are self-declared and voluntary, although all Arup employees are encouraged to complete a free text box in their personal profile, describing their expertise, and to update this every three months. This practice is reinforced by the annual appraisals, in which the personal profile is used as a first measure of compliance with the 'knowledge competency' element of the appraisal. Three monthly 'prompts' remind individuals to keep their profiles up to date.

The profiles highlight areas of expertise, areas of interest and relevant publications. With the exception of the appraisal, entries are largely self-validated, and a high degree of trust exists that individuals will be honest and accurate—an approach that is typical of the culture and ethos of this organization, but would not be embraced by more formalized, structured firms. There is strong social pressure for staff not to 'over-declare' their skills. Indeed, the declaration of an individual's skills is based on the statement 'what things I expect people to ring me up and discuss'. This approach places the burden on the professional to be able to answer technical questions in the areas declared as skills when asked to so by their colleagues. The result of this approach is that most Arup staff have not only completed their profiles, but provide detailed and technically precise information on their expertise and skills. They also share extra information about their leisure and out of work interests and activities, which have proved a useful source of new skills for the organization. Within Arup, the free text entered is analysed by a search engine that probes the largely unstructured text fields and enables access for members of the firm to detailed and relevant technical expertise.

In order to utilize this information, this paper draws on semantic network methods. Semantic networks involve labelling nodes, and links between these nodes, that lead to structures (Sowa, 1987). There are several different types of semantic networks depending on the types of relations between concepts, which can be words, composite words and/or phrases. An automated or semi-automated semantic network approach to textual analysis is map analysis (Carley, 1993) or knowledge graphs

(Popping, 2003). Map analysis focuses on concepts and the relationships among them. It incorporates a number of techniques, which vary according to the nature of the relationship studied: linguistic–semantic, semantic, and proximal. The linguistic semantic approach to map analysis assigns units to semantic categories, such as actor, action, object, time, space, process, and event (Wilks, 1989), and represents text in terms of relationships among these categories. This approach is appropriate for examining sequences of actions (Carley, 1993), but it often deals with toy-like data sets (Danowski, 1993) and, therefore, is not easy to apply to large-scale textual analysis. It is also not suited to generating graphs or numerical text evaluations (Carley, 1993).

In contrast, semantic-based textual analysis uses concept types (such as people, places, actions, objects) and four different characteristics of relations: directionality, meaning, sign, and strength (Carley, 1993; Popping, 2003). This is a very flexible approach to text analysis; however, mathematical and statistical techniques for analysing such a network are not fully developed (Carley, 1997). Also, because this approach retains a large amount of information on both concept types and relations, it is harder to automate the textual analysis process. As Carley (1993) suggests, this approach is not appropriate for representing knowledge in exploratory research, or in situations where there is no theoretical reason to distinguish between types of relationships or concepts.

An alternative semantic network approach is proximity analysis (Danowski, 1982). Within this approach a relationship is established between two words, in the event that they occur within some specified window 'n' word position wide which slides through the text, counting and aggregating all word pairs within the window. For example, when the window is set equal to one, word pairs are constituted only of words that appear next to each others. The direction, the sign and the meaning of a relationship cannot be captured by this approach, but the strength of the relationship can be measured by the number of times two words are proximal or by a normalized measure of this count. Proximity textual analysis is very similar to 'co-word analysis' (Callon et al., 1986; Healey et al., 1986; Callon et al., 1991; Law and Whittaker, 1992; Courtial et al., 1993; Peterson, 1993; Leydesdorff, 2005; Leydesdorff and Hellsten, 2005). While co-word analysis examines the co-occurrences of two words in some unit of text, proximity analysis counts the number of times each word in the text occurs at a certain distance from other words.

Given the exploratory nature of our research setting, we use a combination of co-word and proximity analysis

to map the knowledge of our research partner. This approach has several strengths in our setting in that it is a semi-automated approach, which allows the industry researcher to make informed choices about which concept to overlook and which multi-word phrase to treat as a simple concept. It does not impose a requirement to specify the theoretical relationship between the nodes, nor does it require manual coding of concepts by categories of knowledge. This is especially important in a case such as ours where there are large numbers of diverse, un-coordinated and often incoherent textual statements. It also allows us to map and compare three different networks: keyword-to-keyword, individual-to-keyword and individual-to-individual. ~~Thus, in our approach a first stage in the exploratory analysis, working with messy textual information, highlights important relationships between concepts, providing insights that automated or labour intensive manually coded approaches would not easily impart.~~ The main disadvantage of this approach is that it can obscure the meaning of words.

The first step in co-word analysis involves identifying keywords from the body of texts in order to build the co-occurrence matrix. In this study, we used the most frequently occurring words in the skills descriptions as keywords. Once the keywords were selected, we were able to derive a person by keyword asymmetric matrix (X) in which cell $x_{ij} > 0$ if the i th person mentions word j th in his/her skill description, and $x_{ij} = 0$ otherwise. This 2-mode matrix can be transformed in a 1-mode keyword-by-keyword symmetric matrix whose ij th cell indicates the number of times two keywords appear together in the skill description. But we can also derive another 1-mode person-by-person symmetric matrix whose ij th cell gives the number of keywords that person i and person j have in common, in their skill descriptions.

In co-word analysis, the 2-mode matrix is an intermediate dataset used to derive the co-occurrence keyword-by-keyword matrix since the focus of attention is to uncover the association between the different subject areas. However, in the context of our study, analysis of both the person-by-person matrix and the 2-mode matrix can provide some useful insights into the skills and capabilities of Arup employees, especially when combined with information on individuals' grade, tenure, and office location.

4. Results

4.1. Analysis of the keyword-by-keyword matrix

We begin our analysis by exploring the content of individual skills declarations available in Arup's exper-

tise location system in October 2004. In total, there are 3131 expert yellow pages and the textual descriptions average 316 characters, but the longest description is 1950 characters long. The skills descriptions are quite broad ("Underground Stations and Subways") and very detailed ("Automotive Industry manufacturing facilities generally from small scale tier 1/tier 2 suppliers up to complete car assembly plants. Particular clients: Delphi, General Motors, Opel, VW, Toyota"). The range of expertise within Arup is very diverse, covering standard structural engineering competences, such as 'bridge inspection and assessment', but also some unexpected skills such 'flying fox relocation', 'granite fountains', 'exhumation', 'film processing', and 'fund raising'.

Using this raw information, we derive the most frequently occurring words, pairs of words and ~~trios~~² of sequential words to be used in the co-word analysis. We assume that certain skills or area of expertise can be adequately represented by a single word, for example 'geotechnics' or 'acoustics', but other engineering skills might be more directly identified by pairs of words such as 'remote sensing' or 'traffic calming' or by triplets of sequential words such as 'computational fluid dynamic' or 'environmental impact assessment' (for an application of this approach see Corrocher et al., 2007).²

We considered only those words, pairs, and triplets that occurred with a frequency of more than 10 times. In selecting the list of 574 keywords used in the co-word analysis we adopted the following criteria. First, words such as 'design', 'project', 'management', 'system', and 'engineering', although frequent in the skills descriptions, were eliminated because on the grounds of being too generic and not identifying skills. However, these words appear in some of the pairs and triplets, i.e. 'risk management', 'sustainable design' or 'building service engineering'. Second, words such as 'health-care', 'industrial' or 'pharmaceutical' were included in the analysis because they refer to specific skills related to a particular client or sector. Third, very frequent single words such as 'traffic' or 'railway' that also appear in pairs or triplets (e.g. 'traffic control' or 'railway signalling') were nonetheless kept as keywords because the occurrence frequency of the pairs or triplets was much smaller than the occurrence as single words.

² To be able to extract pairs and triplets of sequential words, we cleaned the skills description texts by removing articles, prepositions, adverbs, verbs and punctuation and by correcting words for plurals. To achieve a list of pairs and triplets we screened all 60,752 items produced by our algorithm and in cooperation with our industrial partner identified those that were meaningful.

Before proceeding with the analysis, we normalized the values in the cells of the co-occurrence matrix using Salton and McGill's (1983) cosine coefficient, where each word pair co-occurrence is defined as the ratio of their co-occurrence and the product of the square root of the respective occurrence frequencies (Leydesdorff, 2005; Leydesdorff and Hellsten, 2005).³ We visualized the normalized co-occurrence matrix using Pajek (Batagelj and Mrvar, 2005) and derived some other structural properties using social network analysis techniques.⁴ In this approach, each word is considered as a node connected by the relation of co-occurrence to another node. The size of the node is proportional to the number of times the word appears in the body of the texts being analysed. The thickness of the line linking two nodes is proportional to the normalized co-occurrence measure, that is, words that appear together very frequently are connected by thicker lines.

The skill map depicted in Fig. 1, offers a convenient graphic summary of the distribution of expertise in Arup. It is clear from the size of the nodes that the most frequently occurring words are 'structure' (376), 'railways' (302), 'steel' (217), 'concrete' (180), 'water' (165), 'project management' (162), 'bridge' (161), which suggests a special focus in these areas. Some of Arup's main areas of specialization are visible as clusters. For example, on the bottom right of the map there is a cluster of fire engineering skills and on the left a cluster of transport related skills.

Although informative about the overall skills in Arup, the co-word map is too complex to be analysed in great detail. We therefore generated clusters of keywords from the co-occurrence matrix using the within groups clustering method with Euclidean distances. We found 20 clusters, which are represented in Fig. 2, where all nodes are shrunk in a cluster to one node whose size is pro-

portional to the sum of occurrence frequencies of the keywords belonging to that cluster.⁵ The value of the line between two clusters has been normalized by the product of the number of keywords in each cluster.

This clustering approach allows us to identify potential synergies among activities in different skills areas. The cluster names reflect the existing business areas in Arup, and were validated by senior managers in the company. Some interesting findings emerge from the grouping of the skills. Expertise in wind engineering, seismic engineering, and automotive design all use similar methods for the analysis of vibration (non-linear element analysis, finite element analysis and structural dynamic) and similar software (Nastran, Lsdyna). Some other connections among different knowledge domains emerge from the clusters map: skills related to environmental engineering and urban planning appear to be strongly associated with skills involved in risk assessment, health and safety, and waste management. Similarly, expertise in acoustics seems to be applied in the construction of public buildings and sport facilities. Water engineering and hydrology are strongly connected, although water engineering and maritime do not appear to have common expertise. This reflects the distinct groups used to run maritime and water business areas in Arup, with different clients, areas of expertise and project type mixes. The analysis also shows that skills in structural and civil engineering and in bridge building, although very important to the firm, do not show a significant degree of overlap with other knowledge domains.

This analysis illustrates the structure of relationships between different areas of Arup's knowledge. It shows that the underlying skills of the organization strongly overlap, beyond the extent envisaged in the organization. It also shows that these overlaps may be a source of competitive advantage for the firm as it seeks to respond to ever more challenging global problems and to find ways to bundle previously distinct areas of activities into cohesive solutions for its clients. Moreover, this analysis identifies the lack of synergies among different knowledge domains that might need to be addressed to improve current performance and drive business growth.

By exploiting information stored in Arup's human resources records we are also able to explore the skills profiles of different cohorts of staff. We compare the skills of 446 junior employees that joined the firm after

³ Both the co-occurrence and normalized matrices were obtained using the software developed by Loet Leydesdorff (downloaded from the website: <http://users.fmg.uva.nl/lleydesdorff/software/fulltext/index.htm>).

⁴ We could have used multidimensional scaling proposed by Peters and Raan (1993), to visualize the co-occurrence matrix; however, social network analysis allows to indicate on the same map the linkages between the words, the strength of the relationship in terms of the thickness of the lines and the occurrence frequency of the words by their size. In addition, as pointed out by Leydesdorff and Vaughan (2006), the Kamada and Kawai (1989) algorithm used to visualize the co-occurrence matrix can be considered as equivalent to non-metric multidimensional scaling. This algorithm assumes that each node is connected by springs to every other node in the network and it works by iterative optimization starting from the initial position of the nodes and their repositioning to minimize the overall 'energy' of the spring system.

⁵ Because of the sample size, we do not report either the dendrogram of the cluster analysis or a list of the words forming the different clusters. However, both are available upon request from the authors.

Arup for

634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655

its interactions with clients, moving away from more traditional engineering practices into more general management and specialist engineering areas. These changes are encouraging efforts to recruit new staff also to retain experts whose skills and experience are valuable and not held by the generations of new staff.

Second, we examined the most frequently occurring words in each network. Among the skills descriptions of junior employees 'autocad' ranks first, and 'water', 'energy', 'environment' are among the top 10 most frequently occurring keywords. The frequency of water, energy and environment reflects the recent growth of these business areas in Arup. The skills of senior employees seem to be focused more around highways, bridges, and airport construction. These are the traditional engineering activity areas, but over time they have become a less prominent part of the activities of the firm as new specialist engineering services areas have emerged, often only distantly related to these traditional areas of engineering consulting services.

Third, we derived some descriptive statistics from these two networks, reported in Table 1. The density of

Fig. 2. Arup skills areas (threshold level of cosine > 0.3).

Table 1
Descriptive statistics of the networks of the skills networks of junior and senior employees

	Junior employees	Senior employees
Density of the network	0.026	0.053
Mean($^{\circ}$)	15.04	30.43
Network centralization	0.168	0.360
Average path length	2.601	1.288

the network, i.e. the total number of linkages divided by the number of possible linkages, and the mean degree, i.e. the average number of linkages, are much higher in the senior employees' skills network than in the junior employees' network. The network centralization index,⁶ which measures the extent to which connections are concentrated in a small numbers of keywords, is also much higher in the network of senior engineers than in the juniors' network. This suggests that the periph-

⁶ This index is equal to the sum of the differences between the largest node centrality score and the scores of all the other nodes divided by the maximum possible sum of differences (Wasserman and Faust, 1994).

eral keywords in the senior members' network are more strongly connected to the keywords in the centre and/or less connected to other peripheral keywords. Finally, the average distance between keywords in the skills network of junior staff is more than twice that in the senior employees' skills networks. All these measures suggest that the skills of senior employees are much more closely integrated than those of junior engineers and that there is a stronger focus among senior staff on core areas of the firm's engineering knowledge. This finding is supported by the analysis of the valued cores in the two networks reported in Figs. 3 and 4. Valued cores identify very cohesive subgroups within the networks. A valued core is a maximum sub-network in which every word co-appears with other words in the text at least a certain number of times corresponding to a certain value of the cosine measure (see Batagelj and Mrvar, 2003, for a formal description of valued cores and an application in a similar context). The skills network for junior staff (see Fig. 3) is very fragmented with clusters of expertise around a number of extremely diverse knowledge domains, including façade engineering, geotechnics, maritime, highways design, acoustics,

Fig. 3. Skills map of junior employees with 6 years of tenure in Arup (threshold level of cosine < 0.3).

microclimate, electrical engineering, footbridge, transport, and logistics. The skills map for senior employees (see Fig. 4) on the other hand, is more cohesive, around fewer areas of expertise: structural engineering, geotechnics, maritime, seismic engineering, railways, tunnelling, bridges, and highways. In some ways, this figure reflects the firm's past projects and the traditional lines of business that have sustained the organization over the past 30 years.

4.2. Analysis of the person-by-person matrix

The previous section provided an overall assessment of Arup's areas of expertise by examining the co-occurrence of keywords. We now shift the focus from keywords, to individuals by analysing the person-by-person matrix. This matrix represents a network with 3131 nodes, where individuals are the nodes, and two nodes are connected if individuals have common expertise in terms of the list of keywords. This way of

representing the information stored in the expert yellow pages enables us to identify both very central individuals with expertise in many different areas and also peripheral individuals with unique expertise.

To better understand this networks, we derived two centrality measures (Wasserman and Faust, 1994):

- *degree centrality*, which measures the number of link-ages of a given node, i.e. the number of skills an individuals has in common with other individuals in the network;⁷
- *betweenness centrality*, which is a measure of how often a node is located on the shortest path between other nodes in the network. Thus, an individual with high betweenness is responsible for connecting many pairs of individuals via the best path; losing that indi-

⁷ The degree centrality of the network is on average equal to 240 with a median of 197 and a standard deviation of 203.

Fig. 4. Skills map of senior employees with at least 10 years tenure in Arup (threshold level of cosine > 0.5).

vidual could result in pairs of individuals becoming disconnected.⁸

The node (individual) with the highest degree of centrality (1091) is a senior engineer with 15 years tenure in the firm and skills in many different areas of structural engineering, ranging from construction of pedestrian subways, offices, a library and multi-storey hotels to constructions in rural areas of Africa and energy piles for art galleries. The node with the lowest degree of centrality (5) is a junior water engineer who joined the firm in 2003 and has unique expertise in ‘determining chaos and non-linear behaviour in real noisy ecological time series’ and in the application of ‘molecular tools in the diagnosis of problems in waste water treatment plants’. The node with the highest betweenness centrality (.0041) is a junior electrical engineer with very broad engineering skills covering the areas of electrical building services, information and communication technologies

(ICTs), heating systems, fire escape, snow build-up prevention, temperature maintenance in tanks and pipes used in industrial processes, power cable joints, and quality assurance auditing. These results enable Arup to identify those individuals with unique combinations of skills, who should be retained by the firm and developed.

We also derived a measure of the ability of individuals to bridge structural holes, i.e. to span different knowledge domains not directly integrated (Burt, 1992). These individuals span a range of knowledge domains from remote parts of the network, and may have the ability to develop new combinations of knowledge. We captured this information by subtracting one from the individual’s network constraint measure⁹ (Burt, 1992), which is an indicator of the extent to which the knowledge domain of a person is directly or indirectly associated with the knowledge space of another person. The individual scoring highest for this indicator is a junior civil engineer who joined in 2001 and has

⁸ The betweenness centrality measure has an average of .0002 a median of .00008 and a standard deviation of .000427.

⁹ The network constraint measure has a mean of .138 and a standard deviation .323.

expertise in civil engineering related to a number of sectors (commercial, retail, industrial, residential, educational, public sector organizations), construction management, 3D modelling, urban environmental monitor, land reclamation, highway safety, construction of car parks, cycle ways, and drainage design.

Another interesting way to analyse the person-by-person matrix is to identify clusters of individuals with similar skills sets. However, standard social network techniques for detecting groups inside a network are difficult to apply in very large networks such as ours. Thus, we derived value cores at different cut-off values and then tested for the presence of components, i.e. disconnected parts of the network. Because the network has a very tight core, we could only identify a valued core (the core with the lowest threshold value) with more than one component. This implies that we can only observe distinct clusters at the periphery of the network. The largest component has 66 individuals mostly in the areas of human resources and project management. The second largest component has 52 nodes and includes quality

assurance and financial administration experts. Other components include sub-networks with 32 actors with skills in ICTs, with 14 individuals specialised in CAD and with nine experts in the 3D software package, microstation. Another subgroup was comprised of six people with expertise in railway signalling.

The approach described above could have some implications for Arup's human resource strategies in terms of which personnel should be retained, the potential impact of a brain drain, locating the most appropriate staff for projects and exploring and exploiting new combinations of skills.

4.3. Analysis of the person-by-keywords matrix

Another very fruitful way of exploiting the information contained in the expert yellow pages is to map the 2-mode person-by-keywords network. Because visualizing the entire network of 3313 individuals and 574 keywords would not convey much information, we selected a few keywords related to fire engineering,

Fig. 5. The 2-mode sub-network of fire engineering related skills.

Fig. 6. The 2-mode sub-network of skill owned by individuals experts in fire detection.

a fast growing specialist engineering area within the firm. We plotted (Fig. 5) the 2-mode network in which we excluded all keywords not related to this area, but contained in the skills descriptions of individuals that identified with this specialism. This resulted in a 2-mode network visualized using NetDraw (Cross et al., 2002) and depicted in Fig. 6 with 13 keywords shown as dark boxes and 155 individuals indicated by circles. There are four large clusters of individuals at the periphery of the network, one related to fire protection, one to fire alarms, one to fire safety and a more isolated one related to fire detection.

We decided to explore the expertise that these eight individuals with expertise on fire detection in more detail to determine what they bring to the fire engineering group. Fig. 7 shows the 2-mode sub-network based on these eight people and the keywords in their skills descriptions.

This type of analysis is extremely useful for identifying people with the expertise to perform on bidding or

project teams. Keywords can be extracted from bid documentation and used in the co-word analysis to derive a two-mode network map. This would allow the bid manager to identify the expertise of individuals outside his/her social network, which is likely determined by geographical or disciplinary boundaries (Monge and Contractor, 2003).

5. Discussion

Many of the tools used to analyse capabilities in manufacturing firms cannot be applied to professional services firms (Henderson and Cockburn, 1994; Eisenhardt and Martin, 2000). Few of these firms patent or produce concrete goods that can be used to build a picture of their underlying capabilities. Because of the range of projects undertaken in different markets, professional services firms are noisy, messy environments in which to develop strategy and firm capabilities profiles. Much of the knowledge inside these firms is not revealed

through conventional tools such as patents and publications. Yet an understanding of these capabilities is vital for firms as market pressures demand that they search for new sources of value. As competitiveness among professional services firms increases, companies such as Arup must continually explore how best to analyse their skill set and to communicate to clients why they should use a firm with 7000 employees rather than one whose list of skills may be similar but which employs only 700 people. They need to demonstrate the value of larger organizations in terms of the breadth and depth of services that can be mobilized and accessed when necessary, something that is not easily conveyed by a summary of top level skills. The techniques developed in this paper enable a far richer depiction of an organization's knowledge, creating the opportunity for larger firms to both understand their true capabilities and communicate the potential value of these capabilities to clients.

By utilizing a tool that is common in professional services firms – the corporate yellow pages or expertise location system – we have developed a map of the firm's skills, and explored the relationships between different areas of skills capabilities. We have attempted to map the 'combinatorial capabilities' that underpin different project activities in professional services firms (Kogut and Zander, 1992). We have applied this approach to produce a visual representation of the patterns of relationships between individuals and groups within the firm, which will allow comparisons to be made between cohorts of staff. This approach identifies individuals with unique skills and that span important knowledge domains within the organization, providing an important insight into the nature of the knowledge held by individuals within professional services firm that other more formal tools are unable to capture. It demonstrates that an individual's knowledge is shared with, and differentiated from, that of others inside the organization.

The methods used in this study could have wide generalizability across a range of professional services firms and would help managers to gain a better understanding of the project skills in their firms, the skills of their individual staff members, and how these might be translated into organizational capability. These methods are particularly appropriate for Arup, where the knowledge profiles of employees are volunteered rather than structured, and where there is a strong tradition of professional autonomy. Bottom-up evolution of skills clusters is more likely to identify skills emerging in response to market needs, than a top-down classification of skills. A more structured skills database would have produced a rather narrow perception of the organization's skills set, and would not have allowed such rich pictures of poten-

tial combinatorial capabilities. There is still potential in exploring the links between existing business areas, but to generate greater value, structured databases need to be supplemented by a more intuitive profiling of people's skills—either through surveys or more direct profiling techniques (e.g. email analysis or project document review to identify knowledge areas from unstructured text).

Given the increased competitiveness in many of the traditional core engineering consulting markets, there is a need to continually re-evaluate and reinvent the knowledge base of the firm (Kogut and Zander, 1992; Grant, 1996; Kogut, 1996). Professional services firms need to constantly move between competitive markets to identify new sources of value that justify higher rates; this requires confidence based on a true picture and understanding of their firms' skills. This study offers a structured technique for identifying the value of knowledge assets, through the linking of clusters of knowledge, allowing the organization to assess both current levels of activity (e.g. based on the profitability within each cluster) and the potential benefits of combining clusters.

This study opens up a range of new research questions and highlights the potential for corporate yellow pages/expertise location systems and other KM systems to be used to gain new insights into the nature of the capabilities in professional services firms. KM systems represent a considerable information resource, which, to date, has not been fully exploited in management research. The information contained in KM systems constitutes a unique and powerful lens through which to view what is taking place within a firm, and how knowledge is being created and shared among its various actors. Such detailed information should enable managers and researchers to better understand the evolution of capabilities, and the role of knowledge in creating competitive advantage, especially in environments where the knowledge often resides in skilled individuals.

In order to gain an insight into the performance implications of the use of knowledge inside the firm, it would be useful, using our analysis, to link the acknowledged capabilities with the financial performance of different groups and individuals within the firm. It might, in future, be possible to explore which bundles of skills are responsible for the growth of new businesses, and/or the profitability of individuals and teams. This knowledge could lead professional services firms to proactively seek to harness the complementarities between skills to realize new value. This approach could also be embodied in an electronic tool that would enable individuals to map their knowledge relative to that of members of their teams, areas, and organization. Such a tool could be used

to translate free-text skills declarations in individual ego networks, where an individual's position relative to others in the firm could be visualized. Individuals could exploit opportunities to build new ties with individuals within their network, who have common interests and knowledge but who may be physical or socially distant in terms of their positioning within the organization.

Although we have exploited a large, unique dataset, and a powerful set of analytical tools, our study is limited to one period and, therefore, we cannot explore changes in skills over time. In addition, our analysis focuses on the most frequently occurring words; unique or less frequently occurring combinations that may be emerging in different parts of the organization will only be identified when they reach critical mass. The present study, therefore, does not capture all the seeds of potential future growth. The mapping of skills and capabilities by means of co-word analysis is especially useful for professional services firms, but it may be irrelevant for other types of firms that rely on the use of capital equipment or more physical technologies. Also, our approach equates word clusters with capabilities, with word combinations representing clusters of skills of individuals. However, the skills of an individual in a professional services firm are often bounded by the nature of work and the types of teams in which the individual operates. At present, we can map only individual skills; however, individuals may be embedded in project teams that represent a range of different skills. The skills encapsulated within a team may complement each other and interact in the performance of a project in ways that our analysis does not capture. Information from KM systems combined with other data sources, may allow us to explore many of these theoretical and empirical possibilities related to the nature of capabilities and knowledge work in professional services firms, in much greater detail.

Acknowledgements

A previous version of this paper was presented at Bocconi University, the Academy of Management, and Imperial College London. The research was sponsored by the Engineering and Physical Sciences Research Council's (EPSRC) IMRC at Imperial College London. Ammon Salter would like to acknowledge the support of the Advanced Institute of Management (AIM) Ghoshal Research Fellowship grant number P01597, sponsored by the Economic and Social Research Council (ESRC) and the EPSRC. The authors have benefited from comments from Loet Leydesdorff, Catelijne Coop-

mans, Jennifer Whyte, Nicos Nicolau, Boris Ewenstein, Jonathan Sapsed, and Toke Reichstein. We are also grateful for insightful and detailed suggestions from the two journal referees. We acknowledge the generous support and contributions of numerous colleagues at Arup.

References

- Argote, L., McEvily, B., Reagans, R., 2003. Managing knowledge in organizations: an integrative framework and review of emerging themes. *Management Science* 49 (4), 571–583.
- Barney, J., 1991. Firm resources and sustained competitive advantage. *Journal of Management* 77, 99–120.
- Batagelj, V. Mrvar, A., 2003. Density based approaches to network analysis. Analysis of Reuters terror news network. <http://citeseer.ist.psu.edu/batagelj03density.html>.
- Batagelj, V. Mrvar, A., 2005. Pajek-Program for Large Network Analysis. Home page: <http://vlado.fmf.uni-lj.si/pub/networks/pajek/>.
- Bettencourt, L.A., Ostrom, A.L., Brown, S.W., Roundtree, R.I., 2002. Client co-production in knowledge-intensive business services. *California Management Review* 44 (4), 100–128.
- Burt, R.S., 1992. *Structural Holes: The Social Structure of Competition*. Harvard University Press, Cambridge, MA.
- Callon, M., Courtial, J.P., Laville, F., 1991. Co-word analysis as a tool for describing the network of interactions between basic and technological research: the case of polymer chemistry. *Scientometrics* 22 (1), 155–205.
- Callon, M., Law, J., Rip, A., 1986. *Mapping the Dynamics of Science and Technology: Sociology of Science in the Real World*. The Macmillan Press, London.
- Carley, K., 1993. Coding choices for textual analysis: a comparison of content analysis and map analysis. *Sociological Methodology* 23, 75–126.
- Carley, K.M., 1997. Extracting team mental models through textual analysis. *Journal of Organizational Behavior* 18, 533–558.
- Corrocher, N., Malerba, F., Montobbio, F., 2007. Schumpeterian patterns of innovative activity in the ICT Field. *Research Policy* 36 (30), 418–432.
- Courtial, J.P., Callon, M., Sigogneau, A., 1993. The use of patent titles for identifying the topics of invention and forecasting trends. *Scientometrics* 26 (2), 231–242.
- Cross, R., Parker, A., Prusak, L., Borgatti, S.P., 2002. Knowing what we know: supporting knowledge creation and sharing in social networks. *Organisational Dynamics* 30 (2), 100–120.
- Danowski, J.A., 1982. A network-based content analysis methodology for computer-mediated communication: an illustration with a computer bulletin board. *Communication Yearbook*, vol. 6. Sage, New York, pp. 904–925.
- Danowski, J.A., 1993. Network analysis of message content. In: Richards, W.D., Barnett, G.A. (Eds.), *Progress in Communication Sciences*, vol. XII. Ablex Publishing Corporation, Norwood NJ, pp. 197–221.
- Davenport, T., Prusak, L., 2000. *Working Knowledge: How Organizations Manage What They Know*. Harvard Business School Press, Cambridge, Mass.
- Davies, A., Brady, T., 2000. Organisational capabilities and learning in complex product systems: towards repeatable solutions. *Research Policy* 29 (7–8), 931–953.
- Davies, A., Hobday, M., 2005. *The Business of Projects: Managing Innovation in Complex Products and Systems*. Cambridge University Press, Cambridge.

- Davies, A.C., Brady, T., 2004. Building project capabilities: from exploratory to exploitative learning. *Organization Studies* 26 (9), 1601–1621.
- DeFillippi, R., Arthur, M., 1998. Paradox in project-based enterprise: the case of film making. *California Management Review* 40 (2), 125–139.
- Dixon, N.M., 2000. *Common Knowledge: How Companies Thrive by Sharing What They Know*. Harvard Business School Press, Cambridge, MA.
- Dougherty, D., 2004. Organizing practices in services: capturing practice-based knowledge for innovation. *Strategic Organization* 2 (1), 35–64.
- Drejer, I., Vinding, A. L., 2004. Organisation, ‘anchoring’ of knowledge and innovation in the construction industry. DRUID Summer Conference, Helsingør.
- Eisenhardt, K.M., Martin, J.A., 2000. Dynamic capabilities: what are they? *Strategic Management Journal* 21, 1105–1121.
- Gann, D., Salter, A., 1998. Learning and innovation management in project-based, service-enhanced firms. *International Journal of Innovation Management* 2 (4), 431–454.
- Gann, D., Salter, A., 2000. Innovation in project-based, service-enhanced firms: the construction of complex products and systems. *Research Policy* 29, 955–972.
- Gann, D.M., 2000. *Building Innovation—Complex Constructs in a Changing World*. Thomas Telford Publications, London.
- Gault, F., Foray, D., 2003. *Measuring Knowledge Management in the Business Sector: First Steps*. OECD, Paris.
- Grant, R., 1996. Toward a knowledge-based theory of the firm. *Strategic Management Journal* 17, 109–122 (winter special issue).
- Hansen, M., 1999. The search-transfer problem: the role of weak ties in sharing knowledge across organization subunits. *Administrative Science Quarterly* 44, 82–111.
- Hansen, M.T., Nohria, N., Tierney, T., 1999, March–April. What’s your strategy for managing knowledge. *Harvard Business Review*, 106–116.
- Healey, R., Rotman, H., Hoch, P.K., 1986. An experiment in science mapping for research planning. *Research Policy* 15, 233–251.
- Henderson, R., Cockburn, I., 1994. Measuring competence? Exploring firm effects in pharmaceutical research. *Strategic Management Journal* 15, 63–84 (winter special issue).
- Hipp, C., Grupp, H., 2005. Innovation in the service sector: the demand for service-specific innovation measurement concepts and typologies. *Research Policy* 34 (4), 517–535.
- Hitt, M., Bierman, L., Shimizu, K., Kochhar, R., 2001. Direct and moderating effects of human capital on strategy and performance in professional service firms: a resource-based perspective. *Academy of Management Journal* 44 (1), 13–28.
- Hobday, M., 2000. The project-based organisation: an ideal form for managing complex products and systems. *Research Policy* 27 (7–8), 871–893.
- Huff, A.S., 2000. 1999 Presidential address: changes in organizational knowledge production. *Academy of Management Review* 25 (2), 288–294.
- Kamada, T., Kawai, S., 1989. An algorithm for drawing general undirected graphs. *Information Processing Letters* 31 (1), 7–15.
- Kogut, B., 1996. What firms do? coordination, identity and learning. *Organization Science* 7 (5), 502–518.
- Kogut, B., Zander, U., 1992. Knowledge of the firm, combinative capabilities, and the replication of technology. *Organization Science* 3 (3), 383–397.
- Law, J., Whittaker, J., 1992. Mapping acidification research: a test of the co-word method. *Scientometrics* 23 (3), 417–461.
- Leydesdorff, L., 2005. The university-industry knowledge relationship: analyzing patents and the science base of technologies. *Journal of American Society for Information Science and Technology* 55 (11), 991–1001.
- Leydesdorff, L., Hellsten, I., 2005. Metaphors and diaphors in science communication: mapping the case of stem-cell research. *Science Communication* forthcoming.
- Leydesdorff, L., Vaughan, L., 2006. Co-occurrence matrices and their applications in information science: extending ACA to the web environment. *Journal of the American Society for Information Science and Technology* 57 (12), 1616–1628.
- Lowendhal, B.R., Revang, O., Fosstenlokken, S.M., 2001. Knowledge and value creation in professional service firms: a framework for analysis. *Human Relations* 54 (7), 911–931.
- Maister, D., 1993. *Managing Professional Service Firms*. Free Press, New York.
- McDermott, R., 1999. Why information technology inspired but cannot deliver knowledge management. *California Management Review* 41 (4), 103–117.
- McKenna, P., Maister, D., 2002. *First Amongst Equals*. Free Press, New York.
- Metcalfe, J.S., James, A., Mina, A., 2005. Emergent innovation systems and the delivery of clinical services: the case of intra-ocular lenses. *Research Policy* 34 (9), 1283–1304.
- Miles, I., 2000. Services innovation: coming of age in the knowledge-based economy. *International Journal of Innovation Management* 4 (4), 371–389.
- Miles, I., 2003. Services innovation: coming of age in the knowledge-based economy. In: Dankbaar, B. (Ed.), *Innovation Management in the Knowledge Economy*. Imperial College Press, London.
- Mintzberg, H., McHugh, A., 1985. Strategy formulation in an adhocracy. *Administrative Science Quarterly* 30, 160–197.
- Monge, P.R., Contractor, N.S., 2003. *Theories of Communication Networks*. Oxford University Press, New York, NY.
- Morris, T., 2001. Asserting property rights: knowledge codification in the professional service firm. *Human Relations* 54 (1), 54–71.
- Nonaka, I., Takeuchi, H., 1995. *The Knowledge—Creating Company*. Oxford University Press, Oxford.
- O’Dell, C., Grayson, C., 1998. If only we knew what we know: identification and transfer of internal best practices. *California Management Review* 40 (3), 154–174.
- Ofek, E., Sarvary, M., 2001. Leveraging the customer base: creating competitive advantage through knowledge management. *Management Science* 47 (11), 1441–1456.
- Peters, H.P.F., Raan, A.F.J., 1993. Co-word-based science maps of chemical engineering. Part I: Representations by direct multidimensional scaling. *Research Policy* 22, 23–45.
- Peterson, J., 1993. *High Technology and the Competition State: An Analysis of the Eureka Initiative*. Routledge, London; New York.
- Popping, R., 2003. Knowledge graphs and network text analysis. *Social Science Information* 42 (1), 91–106.
- Prencipe, A., Tell, F., 2001. Inter-project learning: processes and outcomes of knowledge codification in project-based firms. *Research Policy* 30 (9), 1373–1394.
- Salter, A., Gann, D., 2003. Sources of ideas for innovation in engineering design. *Research Policy* 32 (8), 1309–1324.
- Salton, G., McGill, M.J., 1983. *Introduction to Modern Information Retrieval*. McGraw Hill, Auckland.
- Sarvary, M., 1999. Knowledge management and competition in the consulting industry. *California Management Review* 41 (2), 95–107.

- Sowa, J.F., 1987. Semantic networks. S.C.S. Encyclopedia of Artificial Intelligence, Part II. Wiley, New York, pp. 1011–24.
- Stankiewicz, R., 2000. The concept of 'design space'. In: Ziman, Z. (Ed.), *Technological Innovation as an Evolutionary Process*. Cambridge University Press, Cambridge, pp. 234–247.
- Suddaby, R., Greenwood, R., 2001. Colonizing knowledge: commodification as a dynamic of jurisdictional expansion in professional service firms. *Human Relations* 54 (7), 933–953.
- Teece, D.J., 2002. *Managing Intellectual Capital*. Oxford University Press, Oxford.
- Teece, D.J., 2003. Expert talent and the design of (professional services) firms. *Industrial and Corporate Change* 12 (4), 895–916.
- Tranfield, D., Denyer, D., Marcos, J., Burr, M., 2004. Coproducing management knowledge. *Management Decision* 42 (3/4), 375–386.
- Tranfield, D., Starkey, K., 1998. The nature, social organization and promotion of management research: towards policy. *British Journal of Management* 9 (4), 341–354.
- Turner, J.G., Keegan, A., 1999. The versatile project-based organization: governance and operational control. *European Management Journal* 17 (3), 296–309.
- Van Aken, J.E., 2004. Management research based on the paradigm of the design sciences: the quest for field-tested and grounded technological rules. *Journal of Management Studies* 41 (2), 219–246.
- Van Aken, J.E., 2005. Management research as a design science: articulating the research products of mode 2 knowledge production in management. *British Journal of Management* 16 (1), 19–36.
- Wasserman, S., Faust, K., 1994. *Social Network Analysis: Methods and Applications*. Cambridge University Press, Cambridge, England.
- Wilks, Y., 1989. *Theoretical Issues in Natural Language Processing*. L. Erlbaum, Hillsdale, NJ.
- Williams, R., 2002. *Retooling: A Historian Confronts Technological Change*. The MIT Press, Cambridge, MA.
- Zack, M.H., 1999. Managing codified knowledge. *MIT Sloan Management Review* 40 (4), 45–58.