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Sources of Ideas for Innovation in Engineering Design

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ABSTRACT

This paper explores the sources of ideas for innovation in engineering design. The paper shows that engineering designers involved in complex, non-routine design processes rely heavily on face-to-face conversations with other designers for solving problems and developing new innovative ideas. The research is based on a case study and survey of designers from Ove Arup & Partners, a leading international engineering consultancy. We examine the role of different mechanisms for learning about new designs, the motivations of designers, problem solving and limits to designers' ability to innovative. We explore how the project-based nature of the construction sector shapes the ways in which designers develop new ideas and solve problems. We suggest that among the population of designers in Arup, there are a number of different design strategies for innovating and that these can have important implications for how design is managed. We locate our approach in the research on innovation in project-based firms, outlining patterns of innovation in firms that survive on the basis of their success in winning and managing projects.

Keywords: engineering design, innovation, tacit knowledge, project-based firms

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1. INTRODUCTION

This paper explores the sources of ideas for innovation in engineering design. The research is based on a case study and survey of designers in Ove Arup & Partners. Arup is a world leading engineering design consultancy, offering a wide range of specialist services, primarily in the construction sector. Using examples from Arup, we explore how designers solve problems, the motivations of engineering designers and the limits they face to the development of innovative designs. The paper suggests that personal, face-to-face interactions remain essential for designers working in project-based environments. The findings reveal that although designers are keen users of Information and Communication Technologies (ICT), they rely heavily on close, personal interaction to solve problems, to develop ideas and to assess the quality of their work. Using the findings of our interviews and survey, we assess the impact of the project-based nature of production in construction in shaping patterns of problem solving in non-routine engineering design. We explore the implications of the research for knowledge and design management.

Section 2 reviews the empirical and theoretical background to the study. Section 3 contains the research method and section 4 presents the case of Ove Arup & Partners. Section 5 presents the findings of the interviews and the survey and section 6 contains the factor analysis. Section 7 summarises the findings, indicating areas for future research.

2. EMPIRICAL AND THEORETICAL BACKGROUND

Surveys of innovation list a wide variety of sources of ideas for innovation, such as clients, competitors, universities, suppliers, other divisions within the same firm, consultants etc. They show that there is considerable cross-industry and cross-country variation in these sources (Arundel, 1995; Klevorick, 1995). But firms primarily rely on information internal to the firm. For external sources, customers, suppliers and competitors were the most highly cited (OECD, 1999). Innovation surveys also provide evidence of the means through which firms access sources of information. The first among these are industrial fairs and exhibitions. Professional conferences are also considered important in a variety of sectors, such as pharmaceuticals (Klevorick, 1995).

Despite the benefits of these large-scale surveys, many unexplored issues remain. For example, they do not probe the variety of perspectives within the firm toward different sources of innovation. This is because most of the literature is based on the responses of one individual, representing the views of the firm, to rate the importance of various different sources of ideas for innovation. Innovation surveys have also tended to rely on the views of senior R&D managers (Klevorick, 1995). They say little about the process of innovation within the firm and, until recently, they have tended to focus mostly on manufacturing firms. Studies using innovation surveys have also rarely been complemented with interview-based case studies.

We offer a complementary approach to large-scale innovation surveys by focusing on a detailed study of the ideas for innovation in engineering design in a single company, Ove Arup & Partners. Engineering design has long been recognised as a key part of the innovation process (Vincenti, 1990). Yet there have been few studies of sources of ideas for innovation in engineering design (Veshosky, 1998; Court et al., 1997). This paper attempts to fill this gap in the literature by combining interview and survey data.

The engineering design process is principally concerned with how things ought to be. It involves thinking ahead creatively in order to make a technical object fitting the requirements of users or clients. This process of creation often involves developing new combinations of existing technologies. Hacker argues that the engineering design problem-solving process evolves through a series of iterative and overlapping phases: from problem identification, through development of different conceptual solutions, to designing a favoured solution and working out details of the physical artefact. Rarely, however, is this process linear. There is feedback and iteration across all stages in the process and this often involves changing the structure of both the organisation of the design process and the artefact itself (Hacker, 1997; Yazdani, 1999).

In the early phases of this process, design decisions are often made under circumstances involving high levels of uncertainty. In this environment, engineering designers rely on rules of thumb, personal preferences formed from past experience and disciplinary training to make decisions. Vincenti argues that designers make “informed guesses” based on past knowledge (Vincenti, 1990; Henderson, 1998). Constant refers to this process of knowledge development in engineering design as recursive practice, a continuous cycle of trial and error focusing on the creation of a physical project and drawing upon the fundamental laws of nature (Constant, 2000).

In this paper, we explore the techniques used by engineering designers to solve problems and to innovate. Our focus of attention is on the use of different sources and techniques for solving problems. We have sought to use the research to contrast the use of new types of ICT tools with more traditional techniques and sources of information for innovation. There is considerable excitement in the technical literature in both the construction sector and elsewhere about possibilities for new ICT tools to alter the way designers work, communicate and solve problems. These new ICT tools include CAD/CAE software, simulation packages, intranets, on-line databases, World Wide Web, video-conferencing and relational databases.

In the innovation studies literature, there is an on-going debate between those who argue that these new packages of ICT tools have the potential to fundamentally alter the design process (see Steinmueller, 2000). Some suggest that these new tools are leading to the codification of the knowledge-set underlying design activities (David, 1995). The new ICT tools allow for virtual exchanges across space and time between engineering design teams. New visualisation software and simulation packages can also be seen to lessen the need for face-to-face contact and tacit experience.

The promise offered by ICTs stems from a number of general features characterising the potential benefits of these technologies, including the ability to automate information processing tasks leading to cost reductions, improved accuracy and faster response times. They also offer the possibility of assisting in providing new types of information about products and processes, enabling firms to establish markets for new services.

Gann’s analysis of the adoption of ICTs in design and engineering over the last 30 years shows that there are two distinct, but overlapping ways in which ICTs have been used by design and engineering firms (Gann, 2000). First, they have been used to support project processes in design and management, providing mechanisms for linking decision-making from early planning and conceptual stages through design, engineering and procurement, to assembly and erection, installation, commissioning and even operation and facilities management. Second, they have been used to assist firms in managing regular tasks relating to their internal business processes. Applications for computer-aided-design (CAD) were amongst the earliest to be used. In the 1960s, the ability to co-ordinate geometric information using computers was developed at MIT. This capability was essential for manipulating design, engineering, surveying and construction data. Programmes were initially highly specialised, running on large main-frame computers with applications oriented towards particular tasks, such as designing steelwork, the analysis of foundations, or planning and locating new buildings and roads. By the 1970s, general-purpose CAD software became available offering users significant advantages in handling general data for architectural and engineering design. The production of drawings and management of design changes were themselves major tasks on large projects, for which tens of thousands of drawings and working details were often produced. Computers presented new opportunities to organise these tasks, potentially saving time and reducing errors. By the mid-1990s, the combination of powerful portable computers and high-performance digital telecommunications provided the technological infrastructure which, in theory, had the potential to revolutionise project-based, one-off, design, engineering and production tasks. It could enable firms to improve performance in different activities organised in temporary projects.

The reality experienced by many firms was far removed from the benefits that had been hoped for. Investment and training costs had been higher than the perceived benefits. In many cases, ‘islands of automation’ had been achieved, rather than fully integrated systems and therefore only modest improvements in productivity were gained (Gann, 2000). In most cases, systems were introduced into traditional organisational structures that hindered the ability to achieve widespread benefits. This resulted in marginal trade-offs in cost, time or quality, rather than improvements in the overall process. Rarely were firms able to transform their business performance.

Other researchers are also sanguine about the impact of the new ICT tools on engineering design. They suggest that despite the increased use of ICT tools in design processes, designers still rely on tacit knowledge and face-to-face exchanges to solve problems and innovate (Bucciarelli, 1994; Henderson, 1999; D'Adderio, 2001). Nightingale suggests that there is little or no evidence that importance of tacit knowledge for design is declining. In fact, Nightingale suggests that new ICT tools may increase the need for personal, tacit skills and face-to-face (Nightingale, 1998).

Steinmueller suggests this debate can only be resolved by further empirical research. Using data from our surveys and interviews, we comment on this debate. The results of the study are more sympathetic to those who argue that tacit exchanges remain the key sources for solving problems and developing innovative ideas in engineering design, but the story we tell is complicated by the project-based nature of production in the built environment. In our paper, we explore how this project-based environment alters the methods used by designers to solve problems and to innovate, also the use of the new ICT tools in the engineering design process in general.

3. Research method

The research was part of a three-year study of the management of technology in project-based firms which involved in-depth collaboration with six companies, including Ove Arup & Partners. As part of this study, we conducted interview-based case studies of different divisions within Arup in the UK and in the Arup Japan Office in Tokyo. In the interviews, we explored patterns of communication among designers and the relationship between designers and the rest of the firm. Two projects were selected for in-depth analysis. They were selected in collaboration with Arup and were seen by Arup to be examples of current practice. In total, 40 interviews were conducted over a two-year period. We also conducted several interviews with firms working with Arup in a variety of capacities: clients, suppliers, research institutions and contractors.

The interviews were used to frame questions for the survey instrument. This was developed with the assistance of the R&D unit of Arup. It attempted to combine the findings of past studies of engineering design with studies of the sources of ideas for innovation (Veshosky, 1998; Henderson, 1999; Perlow, 1999). The list of sources of ideas was developed after consultation with Arup staff. The survey aimed to compare and contrast use of traditional forms of problem solving, such as sketching on paper, with newer methods, such as searching on the internet.

The survey was distributed to a group of leading engineering designers within Arup’s building engineering division based in London, England and Arup Japan. We received 112 responses to our survey and all those who were asked to participate completed the survey. The designers who participated in the survey are involved in highly complex, non-routine design. The Arup engineering division has been involved in a large number of new, innovative structures, such as the Millennium Bridge in London and HSBC Tower at Canary Wharf. The research team also attended workshops with Arup designers. These workshops focused on exploring ways of developing more innovative designs. As part of these workshops, the research team presented the findings of our interviews to designers. The results of the survey were shared with Arup and comments from senior staff about the findings of the survey have been incorporated in our analysis.

4. THE CASE STUDY ORGANISATION: OVE ARUP & PARTNERS

Ove Arup & Partners is a world leading design consultancy, providing a wide range of services to the construction process, including structural engineering, electrical and mechanical systems, and environmental controls. They aim to translate the idea of the architect into a form that can be constructed and operated effectively. Arup has more than 6000 staff, located in 77 countries. The firm is made up of divisions of 70 to 100 designers, located either along geographical lines or specialist functions.

The founder of the company, Ove Arup, had strong views about engineering and his business and engineering ethics influence the culture of the firm today. Ove Arup believed that engineering has a social function and that engineers should seek to use their technical skills to support improvements in social conditions. He sought to achieve the ideal of ‘total design’ – the unity of all disciplines, actors and activities in the construction project into a total whole focused toward the delivery of socially useful projects.

The environment in which Arup the firm operates places limits on the development of a community as envisioned by its founder. Construction activities are largely project-based. Teams of independent firms join together in a project team that usually disbands at the end of the project. The project-based nature of activities means organisations working in the sector often struggle to learn from project to project. Projects are often one-off and task-oriented. Learning in one project is rarely fed-back to the organisations, as project teams operate semi-autonomously and outside the boundaries of the firm (see Gann and Salter, 1998). Design activities are often undertaken under severe time constraints and this lack of time acts as a barrier to innovation. Veshosky (1998) quotes one engineer describing learning in this project-based, time-pressurised environment in construction like “trying to get off a galloping horse”. At any one time, Arup is working on over 3000 projects across the world. Each regional or divisional office operates with a large degree of autonomy. (Veshosky, 1998)

Arup sees its key advantage over competitors as being the ability to combine a wide variety of specialist skills on projects. Many of its competitors are small, specialised suppliers of design services with few competencies across a wide range of specialist fields (Interviews, 1999). Another of Arup’s advantages is its ability to recruit talented graduates. Students are attracted to Arup because of its corporate philosophy and its participation in complex and demanding projects. Arup employs 450 new graduates per year and its growth strategy has been based on organic, internal development. In some respects, Arup has found itself in a virtual project-based cycle: high profile projects come to the firm because of its reputation for problem-solving, and highly skilled engineers are attracted to the firm because of its ability to win complex, exciting projects. As one interviewee commented, his work does not often involve working on prestige projects, but there is enough to keep it interesting. Arup has a reputation for “creativity in problem solving” (Interviews, 1999).

Figure 1: The generative cycle of projects

As part of this virtuous project-based circle, Arup continues to win high profile, key projects. The generative project cycle is shown in Figure 1. We “get problems that others don’t”, one interviewee commented. Interviewees argued that Arup has gained a reputation for “delivering difficult projects” and for working with leaders in their fields (Interviews, 1999). In part, the strength of Arup’s reputation is based on close, personal relationships among architects, clients, and Arup staff. Relationships that have been built from working on past projects and also by high levels of trust in the ability of Arup to offer high quality design services. Clients are attracted to Arup because they want access to these key individual designers. Arup wants to become a “total problem solver,” weaving together its diverse specialist skills (Interviews, 1999). To respond to changes in the construction industry, Arup has tried to adopt a more client-focused view of its activities.

In order to achieve its model of a total problem solver, Arup has invested heavily in information and communication technologies. Investments in these technologies have not only supported direct design activities, such as the development of simulation models, but also supported communication among the various parts of the geographically dispersed firm. In some respects, Arup is becoming a “software house” for the development of new simulations of buildings and structures, including acoustics, lighting, heating, movement of people, etc. The business is expanding in areas outside the original core business of structural engineering and it has now become a multi-technology design firm working in areas as diverse as fire engineering, car crash-test worthiness and earthquake design.

Because of its wide range of projects and involvement in complex, technically demanding building, Arup is able to use its everyday projects to build new competencies. Designers act as “practitioner researchers” (Groak, 1989). They do research to solve the problems they face in practice and turn this research into future competitive advantage for the firm. Arup also uses the project-based nature of production of the industry to its advantage, using problems on individual projects to fund research into new technical areas. Clients are asked to pay for these research activities because they are essential to their project, but the lessons of this research are adopted more widely within the firm and provide a key source for developing new ideas. Working on a series of complex and innovative projects provides Arup with an environment for building these new capabilities. For example, its work on simulating the capacity of nuclear fuel flasks to withstand impact whilst in transit enabled the firm to develop its expertise in the simulation of car crash safety.

Although Arup works on a large number of complex, one-off projects, not all of its design activities are complex and non-routine. Within the firm, designers see their activities as being divided between creative and operational design. Both forms of design can be a source of innovation, interviewees argued (Interviews, 1999). Creative design is easily recognised as it involves developing new concepts, structures and activities. Yet operational design is more common and it involves getting a design to meet with standards, safety and other regulatory conditions. Most designers do both forms of design. The design tasks differ between projects and over time within a project. Creativity is not limited to creative design and, in some projects, the creativity comes in making designs fit standards for safety and environmental performance.

5. DESCRIPTIVE ANALYSIS OF SURVEY AND INTERVIEWS

5.1 Ideas for innovation in engineering design

In our research, we have attempted to explore the importance of different sources of ideas for designers. Since most of the projects which Arup designers are working on involve the creation of a bespoke product, past experiences can help to guide their design activities, but the creation of the design itself involves considerable new design work. The survey results suggest that Arup designers rely on close, personal relationships for developing ideas in this design work (Table 1). The two highest rated sources of ideas for engineering design were related to face-to-face contact and working with others on projects. Previous experience was cited by over 70% of the sample.

The results of the survey are supported by the interviews of Arup staff. In the interviews, Arup designers indicated the importance of close contact with others within their team and more widely within the firm. There was considerable interchange between young inexperienced designers and more experienced staff. Younger staff relied on their immediate superiors for guidance and support. They had the confidence to bring problems, misunderstandings and confusion to senior colleagues who were close at hand and ready to assist in solving the problem (Interviews, 1999).

Table 1.

Relatively, few Arup designers (37.7%) found talking to clients to be an important source of ideas in engineering design. One interviewee commented that clients were too far removed from the everyday problem of design to be useful in developing ideas. “They are often too far away from the process to talk face-to-face about complex, technical problems” (Interview, 1999). The line of problem solving in design in Arup links individual designers to their colleagues, but rarely to clients or end-users. More often this is the role of the project manager who acts as the gatekeeper of clients’ views. This finding of our survey was a point of concern within Arup itself and goes against their vision of being a more client-focused firm. Another possible reason for this lack of client focus among designers is related to the motivations of designers, an issue explored in the following section.

Despite the fact that Arup is among the highest spenders on ICT tools in the UK design-engineering sector, only 25% of its designers found on-line databases and working with new equipment and software to be important an a source of ideas for design. This was also true for libraries and fairs or exhibitions.

Our interviews suggested that even in environments where designers are working on complex projects, much of the activity in which they are engaged is routine design. Arup designers described their work as often “mundane, routine, standard work”. As one engineer said, design activities involve “the same thing with problems”. Interviewees argued that even in this environment of grubby and pedestrian design activities; they relied on face-to-face contact with colleagues to develop their designs.

The interviews might help to explain these findings from the survey. Within Arup, young designers felt some degree of awkwardness in contacting other people within the organisation. The first place to resolve design problems is through their immediate supervisor.

> Some senior designers provide a client perspective. Others provide an engineering perspective. Supervisors act as a mentor. He would send me off. I did most of the work. He would give me comments. On the civil engineering side, it is generally the same thing, just try to do it (Interview, 1999).

5.2 Motivation of designers

What motivates designers in their work? The results of our survey show that there is no single factor that motivates designers. All factors listed on the survey were seen to be above the half-way point of the five-point likert scale indicating a relatively high level of importance ascribed to all motivations. Interviewees argued that one of the most defining features of working in Arup has been the opportunity to be creative and the feeling that the firm operates with a high level of professionalism in its engineering activities. The overall agenda of the firm and its founder has resonance in the results of the survey. Like many other professions, Arup designers are motivated by a sense of professionalism, problem solving and opportunities to be creative (cf. Becher, 1999).

Table 2.

Working in a team, meeting client needs and creating new structures and buildings also provided motivation to a significant proportion of the sample. Less than half the respondents, however, were motivated by re-using past experience, peer recognition and improving the work of others, yet these activities are essential parts of the design process. The interest in new, creative design activities is consistent with the studies of designers in other industries. Busby found that relatively few designers find rework, re-using past experience and correcting other peoples' mistakes interesting and rewarding (Busby, 1999). Our survey confirms this finding.

5.3 Solving problems in design

In order to explore the importance of different techniques for solving problems in design, our research asked designers to rate the importance of a variety of sources of problem solving techniques. This list of techniques was developed from interviews with designers and a review of the background literature. It aims to contrast the use of ICT tools with more traditional mechanisms for solving problems. The results of the survey indicated the widespread and continuing importance of personal exchanges among designers. The most highly cited method for solving problems was face-to-face conversations with Arup colleagues.

Like Henderson (1999), we found that sketching on paper is a widely used technique for solving problems in engineering design. Even in environments where there is a high level of CAD-usage, designers found sketching to be a useful way to solve problems. Henderson argues that sketching remains important because it helps engineers develop visual ideas and to communicate these visual representations to others (Henderson, 1999). Our study supports the findings of her study.

Table 3.

After sketching, Arup designers solve problems by working with others in their project teams and using their analytical engineering skills. Yet only a third of respondents indicated that face-to-face conversations with clients were an important method for problem solving.

Arup designers also benefit from working alone. Perlow (1999) found a similar situation among software designers. Software designers need time both for social interaction and for working alone, or what she called ‘real engineering time’. Perlow showed that designers need to talk to colleagues for help on immediate problems, but they also need long periods of concentrated effort to perform their engineering tasks (Perlow, 1999).

Our survey shows that few designers used electronic scouting or CAD programmes for solving problems. In fact, only 24.5% of designers indicated that electronic scouting was important in solving problems in design and even fewer designers used CAD. Why is this so? Interviewees suggest that these media lack the immediacy or usefulness of other forms of communication (Interviews, 1999). As previously mentioned, Arup designers are intensive users of electronic tools, but these tools are not nearly as useful as more traditional forms of communication for solving problems. Arup designers felt that the information posted on websites and intranets was of limited value to help them resolve their problems in the design process. They were more willing to speak to colleagues within Arup and others with whom they worked on project teams (Interviews, 1999). The use of CAD systems for solving problems was even more dramatic. Here only 9.8% of respondents indicated that they were important for solving problems. Some of the reasons for this finding are explored in section 7.

5.4 Limits to the development of innovative designs

In the survey and interviews, designers were asked to describe what limits their ability to develop innovative designs. Survey respondents indicated that time, cost, and too many projects limited the development of innovative designs. Of these factors the lack of time was rated important by 75.9% of respondents. Interviews showed that designers faced a constant cycle of overwork, falling behind, and catch-up in Arup. This pattern of work can be found in the experiences of designers across a number of industries and Arup designers are no exception. The pressures of project-based work often result in the need for heroics in order to enable projects to be completed on time and to cost – see Figure 2. For example, Perlow showed that software engineers face similar work pressures (Perlow, 1999). The reason for this pattern of work is related to the way engineering problems are solved by close personal interactions and by working alone. This can lead to constant interruptions that limit time for working alone (Perlow, 1999).

Figure 2 – Project constraints and heroics in delivery

Table 4.

The lack of interest among clients and inability to feedback from end-users was only seen as a problem by 43.1% of respondents. This might suggest that Arup designers do not place high levels of attention on the feedback from end-users. One reason for this relative lack of attention to clients and end-users relates to the way problems in design are organised. Interviewees felt that their design work was often limited to what they called “engineering”. “Nine out of ten problems are determined by architectural forms, material, and structure”. In this environment, Arup designers felt that they were “responding, not engineering” (Interviews, 1999). They were called into projects when the architect had already decided the main design issues and ended up “designing to specifications”. This limited flexibility and opportunities for innovation in the design process. It confines the engineering design process to operational design (Interviews, 1999).

Interviewees also argued that the project-based environment of construction limited opportunities for learning.

> Projects go out to tender and not all issues are addressed. Issues get pushed aside. The level of design is ‘sufficient’ for contractors. Sufficient information, but it will have to be reviewed when it comes to construction. It won’t get done. There is no time to do it. There are too many pressures. It is the nature of the business. You chase around. There is no interest for Arup to put resources at the beginning. There is no benefit to us. It would be a benefit for us to have less conflict, less problems and less supervision on site. But do clients want to pay for this? (Interview, 1999).

One of the reasons for these time pressures is the lack of experience among young designers. For more experienced designers, errors are “stored in memory banks” (Interviews, 1999). A senior designer commented about young designers “they don’t see the whole thing. They see 1/8 of the job. They look at it in isolation. Errors occur in the interfaces.” Another senior designer felt that within the company there were “too many engineers doing technicians’ work” (Interviews, 1999).

Arup designers appear to be well served by the capabilities within their organisation. They also saw few management problems that limit the development of innovative designs. The survey showed that few Arup designers thought access to information was a barrier to their design activities therefore improvements in the information system for designers, such as Intranets, may have little impact on the development of more innovative designs. This finding questions the relevance of knowledge management strategies designed to support access to information for designers. As Court et al. have suggested, few designers lack information, instead what they lack is time (Court et al., 1997).

6. Factor analysis

In order to further the descriptive analysis, we conducted a principle component analysis. Principle component analysis attempts to identify the underlying variables or factors that explain patterns of correlations within a set of variables. It helps to reduce the number of variables by preserving maximum variability of the original variables between observations. A small number of factors can describe the variance observed in a much larger number of variables. A conventional correlation analysis between variables generated considerable levels of correlation. These patterns were difficult to interpret. The use of principle component analysis allows us to more clearly explore the main relationships inside the data set. We conducted a principle component analysis for each of our main questions and then ran a correlation between these factors.

In the principle component analysis for the sources of ideas for design, there were 5 factors that explained 69 percent of the total variance. They included:

- EXTERID – This variable expresses the relationship between external sources of ideas for designers. It reflects the outward characters of many designers’ strategies for developing new ideas. It reflects their reliance on a wide number of different sources of ideas for design outside the firm.

- TACITID – This variable is a combination of talking to colleagues, working with others on projects and previous experience. It can be seen to reflect a tacit design strategy, including a high degree of social interaction and reliance of past experience. There is a negative value ascribed to on-line databases, new equipment and in-house libraries.
- ELECTID – This variable indicates the use of technical sources of ideas, such as on-line databases, in-house libraries and new equipment. It also reflects the need to talk to others outside the firm. There is a negative impact of reading trade journals, previous experience and visits to other building sites.
- CLIENTID – This variable refers to the importance of working with clients, previous experience and working with new equipment. It also reflects the lack of importance of visits to other sites and in-house libraries.
- SELFID – This variable indicates the high degree of importance ascribed to working by yourself and to a lesser extent visits to other buildings sites. There is a negative relation to talking to clients.

Table 5.

In the creation of factors for motives of designers, two factors emerged that explained 43 percent of total variance.

- ALLMOTIVE – The first factor reflects the importance of all motives for design, especially important here was professionalism and working in a team.
- CREATIVE – The second factor reflects designers' interest in creative work and their lack of interest in working with clients, professionalism, improving the work of others.

Table 6.

In the analysis of factors for solving problems in design, three factors emerged. These explained 56.9% of the cumulative variance in the data. They include:

- CLIETECH – The first sector represents the importance of working with clients and others outside of the firm and the use of CAD and electronic scouting.
- TACPROB – This variable reflects the use of face-to-face conversations with the firm, sketching on paper, the use of engineering skills and working alone for solving problems. It is related negatively to the use of CAD and electronic scouting.
- ELECPROB – This variable is positively associated with the use of electronic scouting and negatively associated with face-to-face conversations with clients.

Table 7.

In terms of the limits to the development of innovative ideas, principal component analysis produced four factors. They were:

- LACKIN – This variable reflects a lack of interest among clients, suppliers and within the firm as a barrier to innovation. It also reflects problems inside Arup towards the support of new ideas.
- TIMECOST – This factor expresses the importance of a lack of time, cost and too many projects on going at one time. It also reflects a lack of feedback from end-users and customers.
- LACKSKIL – This variable is positively associated with lack of skills inside the firm and poor access to information. It is negatively associated with inability to get feedback from users and lack of interest among clients.
- LACKCLIE – This variable shows a lack of interest among clients and suppliers, yet a negative associated to long-administration and poor co-ordination inside the firm. It can be seen to represent a lack of interest without the organisational problems associated with LACKIN above.

Table 8.

Using these different factors, we conducted a correlation. Figure 3 illustrates these relationships. The results show that there is a strong relationship between TACITID and TACPROB, reflecting the complementarity between the use of face-to-face sources for both gathering ideas and for solving problems. There was a strong relationship between desire for creativity (CREATIVE) and the use of face-to-face sources for ideas and problem solving (TACITID and TACPROB). TIMECOST was also associated with TACITID and TACPROB. This suggests that those designers who have problems with time, cost and too many projects are also users of face-to-face interactions to solve problems and to gather ideas in design. TACITID and TACPROB were also associated with ALLMOTIV indicating the general link between the use of face-to-face contacts and wider motives of engineering, such as professionalism and problem solving.

Figure 3.

There was a negative association between TACITID and TACPROB, on one side and LACKIN, on the other side. This reflects that designers who use face-to-face sources find few barriers to innovation in design from a lack of interest by others within the firm and outside the firm. There was also a negative relationship between TACPROB and LACKSKIL representing the overall results that users of face-to-face sources find fewer organisational problems as a barrier to innovation. Instead the greatest barriers these designers face is a lack of time and too many projects as evidenced by the relationship between TIMECOST, on one side and TACPROB and TACITID, on the other. There was also a negative relationship between the use of electronic sources of problem solving (ELECPROB) and the use of face-to-face for generating ideas (TACITID). This shows that for those designers who found face-to-face contact useful for generating ideas in design, they rarely used electronic sources to generate new ideas.

There was a strong relationship between designers who found clients as a useful source for problem solving (CLIENTECH) and for generating ideas (CLIENID). This contrasts with the negative relationship between CLIENID and CREATIVE, indicating for those designers motivated by creating new buildings and structures, they relied little on ideas from clients.

There was significant relation between the use of electronic sources for problem solving (ELECPROB) and for idea generation (ELECID). In part, this reflects the overall findings of the correlation analysis that there are some designers who are users of electronic sources for problem solving (ELECPROB), but do not rely on face-to-face contacts for generating ideas (TACITID). There was a negative relationship between those designers who were motivated by creativity (CREATIVE) and those who found that a lack of skill within the organisation acted as a barrier to innovation (LACKSKIL).

Overall, the results of the factor analysis and correlation analysis show that there are different approaches to solving problems among Arup designers. For those that rely on tacit sources for problem solving and for generating ideas, electronic sources are particularly valuable. Time, cost and too many projects act as a major barrier to those designers who rely on face-to-face interaction. A lack of interest or lack of skill among the organisations were negatively associated with creativity and face-to-face problem solving. This suggests that those designers who work in face-to-face contact with their colleagues are motivated by creativity. Any lack of skills in Arup does not act as a barrier to innovation.

7. Conclusions

The research shows that although designers may be keen users of the new ICT tools, they still rely on personal exchanges and visual communication for the difficult parts of their work. This finding is supported by historical and ethnographic studies of engineering design that have shown that face-to-face communication among designers is necessary when there is a high level of uncertainty in the engineering design process (Henderson, 1999; Bucciarelli, 1994). This is especially the case for preliminary stages of design (Veshosky, 1998). Court et al. (1997) found that even when designers work on-line, a number of face-to-face meetings are necessary to build up trust to enable successful collaboration. Our survey validates the widely held belief that implementing ICTs is not a simple substitution for older forms of communication.

Our detailed analysis within a single firm reveals more understanding of the processes and use of tools of design than can be found from more general industry-wide surveys. Studies inside the firm combining interviews and survey data cast new light on patterns of problem-solving and idea formation in innovative environments. This study has shown co-existence of different technical forms of problem-solving. The promise of ICTs has not been realised in its all-embracing form. These tools have not so far become a substitute for more traditional forms of communication. On the contrary, our evidence suggests that ICTs are being used in combination with other forms of communication and problem-solving in engineering design.

Our study confirms the Court et al. (1997) view that designers suffer from information overload. New ICT tools have tended to increase the amount of documentation in the design process. Personal contact is essential to sift through this mountain of information. Like Henderson (1999), we found that designers used mixed practices, switching between paper and computer. Engineers are protective of their social culture of shared decision-making and problem solving. The immediacy of sketching and face-to-face exchanges is a key part of how engineering designers solve problems [Perlow, 1999]. New ICT tools have not yet altered the interactive nature of the design process. Designers jealously guarded their visual and personal exchanges. This was done not as a way of protecting themselves from the development of new technologies, but as a way of preserving the main sources of problem solving available to them.

The findings of our study question the attempts to introduce information-based knowledge management strategies in professional organisations. Designers rely on their colleagues and themselves to help them solve problems. The current set of electronic information sources that are available appear to be of limited value for designers solving problems and developing new innovative ideas in design. This suggests the knowledge management tools that support information access and electronic-mediated exchanges will have limited impact on the innovation process in engineering design. To be successful, a knowledge management strategy should attempt to support team working among designers with some degree of face-to-face interaction.

Our findings also suggest that to support innovation in project-based environments such as those in which the Arup designers work, more focus needs to be placed on time management. Designers felt that time pressure was the main factor that limited innovation. Innovation in this environment of constant project work was like “trying to get off a galloping horse” (Veshosky, 1998). Overcoming this cycle of crisis and catch-up is a key challenge for firms working in project-based environments. Greater attention to allowing time for designers to resolve problems at an early stage of design process could have significant benefits for designers and their clients.

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Table 1. Sources of ideas for design activities, Ove Arup & Partners (n=112)

Sources	% of Respondents[1]	Mean
Talking to colleagues	84.0%	4.2
Working with others on projects	81.2%	4.1
Previous experience	73.2%	4.0
Visits other buildings and/or worksites	58.1%	3.7
Working by yourself	53.6%	3.6
Reading trade or professional magazines	38.4%	3.2
Talking to clients	37.7%	3.3
The work of competitors	36.7%	3.2
On-line databases	25.9%	2.7
In-house libraries	22.3%	2.8
Working with new equipment/software	21.5%	2.8
Fairs or exhibitions	17.9%	2.5

1. Percentage of respondents indicating important (4) or very important (5) on the survey.

Source: SPRU Survey of Design, Ove Arup & Partners

Table 2. Motivations of design activities, Ove Arup & Partners (n=112)

	% of Respondents[1]	Mean
Solving problems	87.5%	4.3
Professionalism, i.e. doing the job right	82.2%	4.2
Opportunities to be creative	82.2%	4.2
Creating new structures and buildings	67.9%	3.9
Meeting client needs	66.1%	3.9
Working in a team	64.3%	3.8
Re-using past experience	41.9%	3.3
Peer recognition	40.2%	3.3
Improving the work of others	34.9%	3.2

1. Percentage of respondents indicating important (4) or very important (5) on the survey.

Source: SPRU Survey of Design, Ove Arup & Partners

Table 3. Techniques for solving problems in design

Techniques	% of Respondents[1]	Mean
Face-to-face conversations with colleagues inside the firm	88.4%	4.4
Sketching on paper	83.0%	4.3
Use of analytical engineering skills	62.9%	3.7
Working with others on the project team from outside the firm	61.6%	3.7
Working alone	40.0%	3.2
Face-to-face conversations with clients	33.9%	3.1
Electronic scouting, i.e. searching through WWW	24.5%	2.7
Trying new designs on CAD programmes	9.8%	2.1

1. Percentage of respondents indicating important (4) or very important (5) on the survey.

Source: SPRU Survey of Design, Ove Arup & Partners

Table 4. Barriers to the development of innovative designs

Limits	% of Respondents[1]	Mean
Lack of time	75.9%	4.1
Too many projects ongoing at one time	62.0%	3.7
Cost	61.6%	3.7
Inability to get feedback from customers and end-users	43.1%	3.2
Lack of interest among clients	32.4%	3.1
Lack of co-ordination among groups within the organisation	30.0%	3.0
Long administration/approval process within the organisation	25.0%	2.6
Lack of interest by others within the organisation	20.5%	2.5
Lack of interest among suppliers	19.7%	2.6
Access to information	18.2%	2.5
Lack of skills within the organisation	12.1%	2.0

1. Percentage of respondents indicating important (4) or very important (5) on the survey.

Source: SPRU Survey of Design, Ove Arup & Partners

Table 5. Principle component analysis of sources of ideas for ideas, Ove Arup & Parterns n=112

	EXTERID	TACITID	CLIENTID	SELFID	CLIETECH
Talking to colleagues	0.256	**0.733**	**0.307**	0.039	-0.041
Working by yourself	-0.123	0.061	0.193	0.309	**0.884**
Talking to clients	**0.511**	0.084	-0.041	**0.572**	-0.289
Fairs or exhibitions	**0.627**	**-0.364**	-0.218	0.052	-0.012
Visits other buildings and/or worksites	**0.571**	0.139	-0.282	**-0.489**	**0.314**
Working with others on projects	**0.312**	**0.772**	0.267	-0.141	-0.047
Working with new equipment/software	**0.419**	**-0.350**	**0.370**	**0.374**	0.097
In-house libraries	**0.553**	-0.299	**0.513**	-0.270	-0.038
On-line databases	**0.776**	-0.135	**0.375**	-0.035	-0.073
Reading trade or professional magazines	**0.632**	-0.140	**-0.473**	-0.046	0.080
Previous experience	**0.351**	**0.437**	**-0.469**	**0.326**	0.011
The work of competitors	**0.683**	0.055	-0.126	-0.058	0.134
Eigenvalue	3.231	1.738	1.330	1.012	1.009
Difference	1.493	0.408	0.319	0.003	0.072
Proportion	0.269	0.145	0.111	0.084	0.084
Cumulative	26.9%	41.4%	52.5%	60.9%	69.3%

Table 6. Principle component analysis of motivations of designers (n=112)

	ALLMOTV	CREATIVE
Professionalism, i.e. doing the job right	**0.637**	-0.291
Creating new structures and buildings	**0.315**	**0.605**
Solving problems	**0.541**	**0.387**
Improving the work of others	**0.508**	-0.253
Working in a team	**0.681**	0.006
Opportunities to be creative	**0.540**	**0.594**
Re-using past experience	**0.433**	-0.296
Meeting client needs	**0.542**	**-0.558**
Peer recognition	**0.471**	0.041
Eigenvalue	2.513	1.419
Difference	1.094	0.455
Proportion	0.279	0.158
Cumulative	27.9%	43.7%

Table 7. Principle component analysis of techniques for problem-solving (n=112)

	CLIETECH	TACPROB	ELECPROB
Face-to-face conversations with Arup colleagues	0.248	**0.688**	0.229
Sketching on paper	0.234	**0.626**	0.091
Electronic scouting, i.e. searching through WWW	**0.423**	-0.245	**0.725**
Trying new designs on CAD programmes	**0.696**	**-0.408**	0.144
Face-to-face conversations with clients	**0.721**	-0.064	-0.253
Working with others on the project team from outside Arup	**0.526**	0.203	**-0.675**
Use of analytical engineering skills	0.329	**0.457**	0.222
Working alone	-0.273	**0.516**	0.078
Eigenvalue	1.759	1.612	1.182
Difference	0.147	0.429	0.244
Proportion	0.220	0.202	0.148
Cumulative	22.0%	42.1%	56.9%

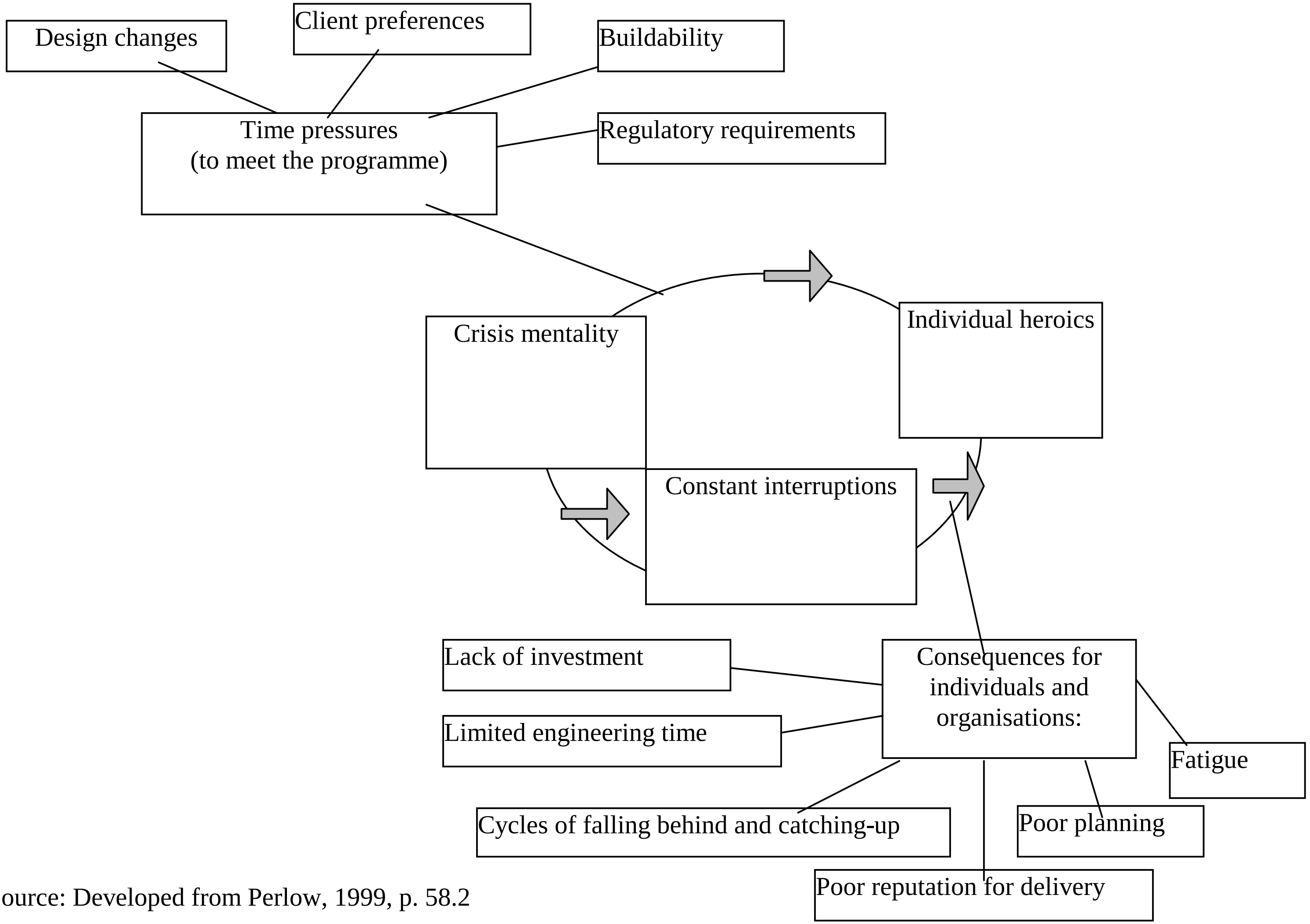
Table 8. Principle component analysis of barriers to innovation in design (n=112)

	LACKINT	TIMECOST	LACKSKIL	LACKCLIE
Lack of time	-0.288	**0.766**	0.051	0.197
Cost	-0.280	**0.619**	**0.444**	-0.004
Lack of interest by others within the firm	**0.672**	-0.009	-0.038	0.253
Lack of interest among suppliers	**0.668**	0.017	-0.207	**0.466**
Lack of interest among clients	**0.461**	0.027	**-0.314**	**0.520**
Too many projects ongoing at one time	0.196	**0.557**	0.178	0.211
Lack of skills within the firm	**0.642**	-0.153	**0.586**	0.119
Access to information	**0.680**	-0.043	**0.509**	-0.147
Long administration/approval process within the firm	**0.730**	0.159	0.016	**-0.431**
Lack of co-ordination among groups within the firm	**0.688**	0.176	-0.204	**-0.398**
Inability to get feedback from customers and end-users	**0.333**	**0.473**	**-0.542**	-0.285
Eigenvalue	3.30	1.59	1.31	1.10
Difference	1.71	0.27	0.22	0.21
Proportion	0.30	0.14	0.12	0.10
Cumulative	30.0%	44.4%	56.4%	66.3%

Figure 1

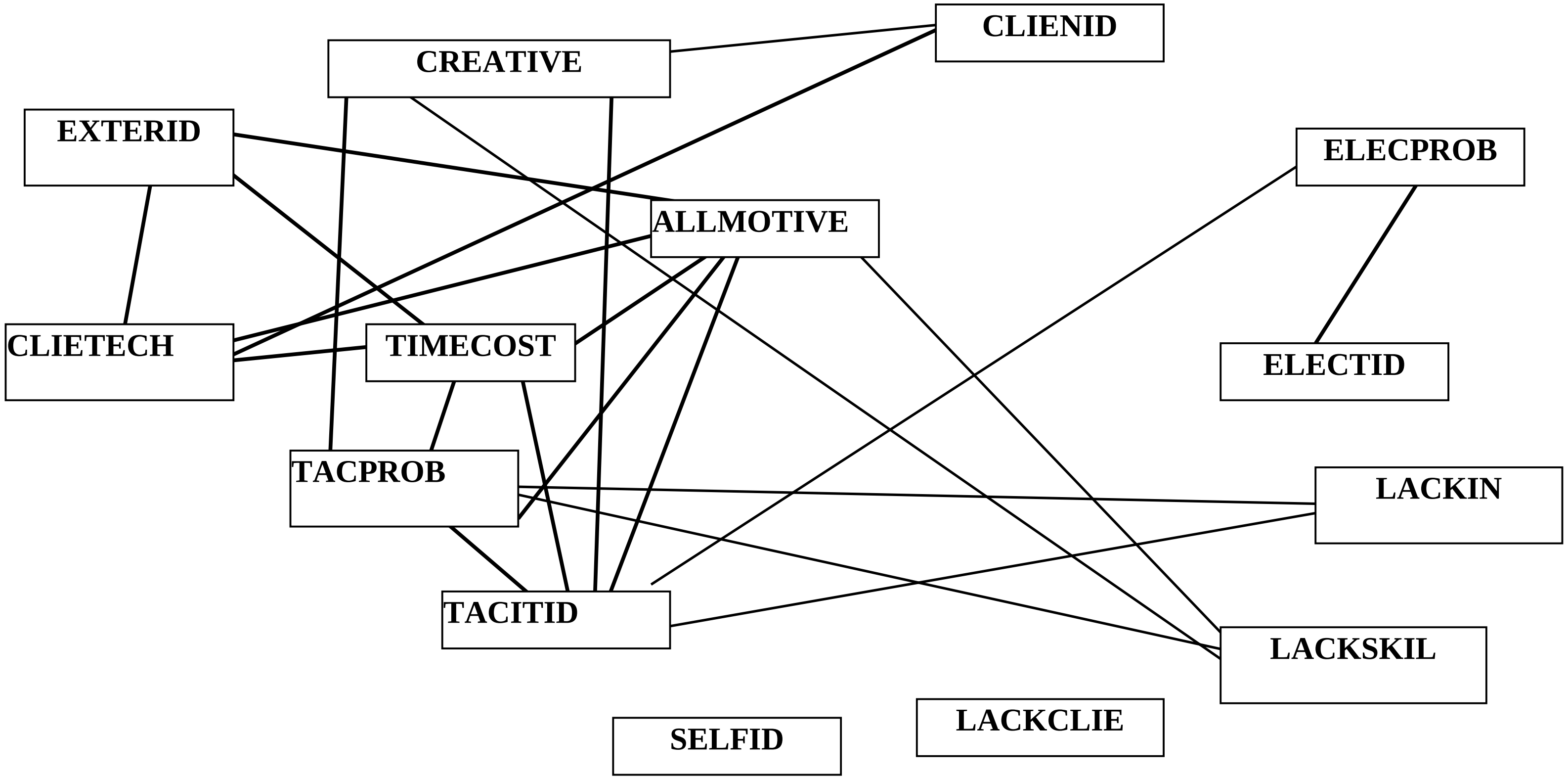
The generative cycle

Figure 2. The designer time-work cycle



Source: Developed from Perlow, 1999, p. 58.2

Figure 3. Correlation relationships between factors among designers (n=112)



Note: Solid line between two factors indicates correlation at confidence level of >.01 and dotted line indicates negative correlation at confidence level >.01.