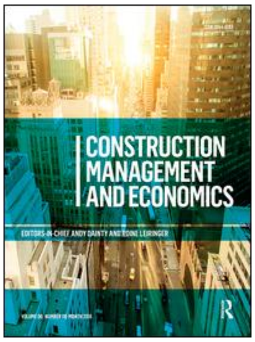

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Jennifer Whyte

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Innovation and users: virtual reality in the construction sector

JENNIFER WHYTE*

Innovation Studies Centre, The Business School, Imperial College London, UK

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Firms in the construction sector act as users of technologies produced outside the sector. This paper considers their role as users and explores their contribution to the 're-innovation' of an emerging information technology – virtual reality. An empirical study of virtual reality use within the construction sector has been conducted using the multiple case study method. Data was collected within 11 lead-user organizations (and four suppliers) and emerging patterns of use are explored. An analytic framework is developed to investigate how two aspects of project-based construction processes – project size and extent of design reuse – affect the technological requirements of users. Divergent requirements are found for the use of virtual reality on different types of projects and, through supplier interaction, these may lead to different families of solutions.

Keywords: Information technology, virtual reality, construction, users, innovation

Introduction

Recent national and international surveys (Fuchter, 1998; Howard *et al.*, 1998; Rivard, 2000) show that information technologies are now widely used throughout the construction sector. Development and production of these technologies, however, usually takes place in other sectors of the economy. Design, engineering and construction firms are users and form part of the wider sectoral patterns of the innovation, adoption and use of these technologies.

This paper considers the role of design, engineering and construction firms as users of one particular emerging information technology – virtual reality. Applications of virtual reality are defined as those that provide an interactive, spatial, real-time medium for visualization. Thus the focus is on graphical computer applications that allow the user to visualize a 3D model and interact with it in real-time. Such applications can be used to visualize data on non-immersive desktop and mobile computers; and in immersive virtual reality centres.

Virtual reality has had a relatively slow diffusion into the construction sector (Bouchlaghem *et al.*, 1996), though the 'pioneers' expected architecture to be a major application. Military, advanced manufacturing and entertainment users were comparatively early adopters of virtual reality. They have heavily influenced early developments in the enabling technologies (Kalawsky, 1993) and virtual reality has become pervasive in aerospace, energy and process-based sectors (Frampton, 2001). Potential applications of virtual reality in construction include: design (Mandeville *et al.*, 1995; Kurmann *et al.*, 1997); construction integration (Alshawi, 1995; Aouad *et al.*, 1997b); and construction scheduling, or 4D-CAD (Fischer and Kunz, 1995; Retik, 1996).

First the wider debates on innovation are considered, focusing on generic technologies and sectors, project-based innovation, and the role of users and producers in innovation processes. From this literature, an analytical framework is developed. A multiple case study of design, engineering and construction organizations is then used to investigate the emerging industrial uses of virtual reality across the construction sector. The results of this multiple case study are used to modify the analytic framework and conclusions are drawn.

*E-mail: j.whyte@imperial.ac.uk

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Generic technologies and sectoral patterns of innovation

The increasing use of IT within the sector can be examined using analytic lenses provided in literature on generic technologies and sectoral patterns of innovation.

Information technologies can be considered as generic technologies as they, like the machine tools used during the mechanization of production, are used widely outside their sector of production – in the production processes of many different sectors of the economy. Such generic technologies are instantiated in similar, but not identical, applications within the complex and idiosyncratic production systems of different sectors and industries (Rosenberg, 1963).

Construction can be described as one sector of a wider economic system. The term 'sector' has been defined as an aggregate of economic subjects: a group of economic organizations, such as firms, which share a common line of business (Archibugi, 1991). Whilst industries are characterized by homogeneity, in contrast sectors are characterized by the heterogeneity of actors (Malerba, 1999). In the innovation literature, concepts such as learning, knowledge, and competencies are seen as central to the definition of a sector and networks and change are emphasized (Malerba, 1999).

The United Nations International Standard Industrial Classification (ISIC) provides one example of a hierarchical categorization of sectors and sub-sectors (United Nations, 1994). In this, construction is represented as a top-level sector. There is not, however, universal agreement about what constitutes a sector, and sectors can be identified at different levels of aggregation depending on the phenomena being studied (Malerba, 1999).

Sectors provide a useful analytic lens through which to examine innovation processes as innovation has been found to exhibit different characteristics within different sectors of the economy. Pavitt (1984) has developed a taxonomy that distinguishes sectors within manufacturing according to the channels through which firms acquire their technological know-how and effect their innovations. Firms are described as supplier-dominated, scale-intensive, specialized suppliers, science based or dependent on public procurement. Though not all researchers agree as to categorization of firms in particular sectors, subsequent researchers have used, extended and refined this taxonomy (Laursen and Meliciani, 2000).

Sectors may also change in nature over time. Any classification of sectors requires continuous updating as a process of growing specialization, complexity and differentiation, brought about by technological change, leads to the identification of new sectors, sub-sectors and industries. This process of differentiation occurs in parallel with the technological convergence that leads to generic technologies and the employment of similar skills, techniques and facilities across sectors (Rosenberg, 1963).

Innovation in a project-based sector

The organizational context of construction innovations differs significantly from a great portion of manufacturing innovations (Slaughter, 1998), which were the focus of the taxonomy proposed by Pavitt (1984). Construction is a project-based sector: firms in the construction sector operate in a project-based manner (Gann, 2000) and conduct innovation almost wholly within projects (Tatum, 1987).

The project-based nature of construction is important for understanding innovation processes within the sector, however we cannot assume that its effect is homogeneous. Within the sector, project-based firms work on a wide range of different types of projects. Firms in some parts of the sector, such as the housing industry, are largely concerned with small projects with extensive design re-use. In these firms, each individual project may only require intermittent staff attention and staff may simultaneously work on a number of projects that are in different stages of development (Whyte, 2002). Much of the sector is concerned with large projects. These projects, which produce capital goods such as large complex buildings and infrastructure, may involve the collaboration of a number of different specialists and organisations over an extended project lifetime (Gann and Salter, 2000).

Table 1 The United Nations ISIC revision 3 top level

A)	Agriculture, hunting and forestry	I)	Transport, storage and communications
B)	Fishing	J)	Financial intermediation
C)	Mining and quarrying	K)	Real estate, renting and business activities
D)	Manufacturing	L)	Public administration and defence; compulsory social security
E)	Electricity, gas and water supply	M)	Education
F)	Construction	N)	Health and social work
G)	Wholesale and retail trade, retail trade, repair of motor vehicles, motorcycles and personal and household goods	O)	Other community, social and personal service activities
H)	Hotels and restaurants	P)	Private households with employed persons
		Q)	Extra-territorial organizations and bodies

Innovations and their users

Innovations rarely arrive fully fledged, able to bring about a rapid reduction in the costs of user organizations (von Tunzelmann, 2000). They are altered, refined and reinvented throughout the diffusion process (von Hippel, 1986; 1988). Users of technologies can be active participants in this process even though they are not directly involved in production. Gardiner and Rothwell (1985) describe users contributing to re-innovation – the process of innovation and product development that occurs after a new product is launched, building upon early success but improving the next generation product with revised and refined features.

In some industries, such as the machine tool industry (Rosenberg, 1963) and the scientific instruments industry (Riggs and Von Hippel, 1994), users have been found to be the major source of product innovations. Machine tools and scientific instruments function as intermediaries in user organizations' products and processes and the users have particular knowledge of their operation. Hence user organizations have the knowledge base upon which to develop improvements (Gardiner and Rothwell, 1985; Marquis, 1988).

The dynamics of re-innovation may be explored by studying the early adopters (Rogers, 1962) or 'lead users' (von Hippel, 1986) of a novel or enhanced product, process or service. Lead users are a subset of early adopters who face needs that will be general in a market place – but face them months or years before the bulk of that marketplace encounters them, and are positioned to benefit significantly by obtaining a solution to those needs.

As generic technologies, information technologies have much in common with machine tools and scientific instruments. They are used as intermediaries in user organizations' products and processes over a wide range of sectors, sub-sectors and industries and we may expect that lead users are a source of incremental improvement and customisation to different market segments.

Analytic Framework

Construction is a project-based process, and the size of projects and the extent of design reuse across projects may affect virtual reality adoption within the sector. These are considered using a matrix of four types of projects as shown in Figure 1:

- small projects with design reuse – these include many office fit-outs and standard housing solutions;
- large projects with design reuse – where the same company or group of companies works on many large projects, reusing design effort across the projects;
- small unique projects – such as architect-designed housing; and
- large unique projects – design intensive projects with many subsystems such as an opera house, airport or shopping mall;

Using the matrix of different types of projects, a theoretical model can be developed to describe the patterns of innovation expected, as shown in Figure 2. In this it is proposed that an increase in project size or the extent of design reuse makes the use of virtual reality more attractive. If the project is too small or has too little design reuse then the benefits of using virtual reality do not outweigh the costs.

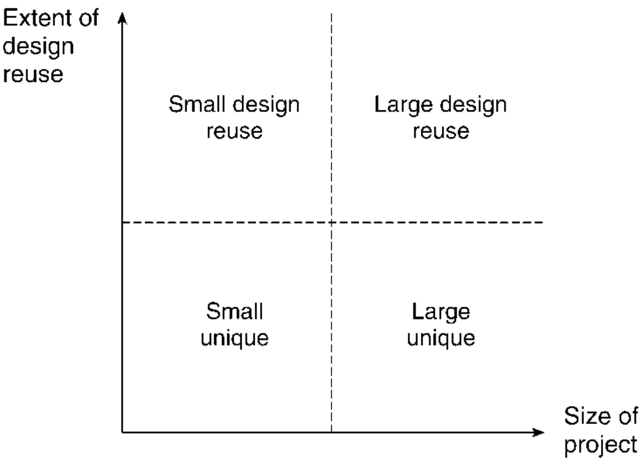

Figure 1 A matrix to show different types of projects by the extent of design reuse on products and the size of the project

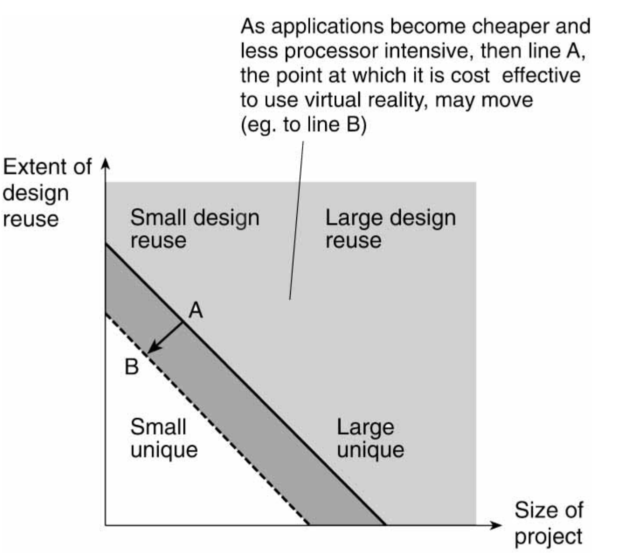

Figure 2 Theoretical model to show projects on which it is cost effective to use virtual reality

In Figure 2, the shaded area represents projects on which it is theoretically beneficial to use virtual reality, line A is the point at which the benefits stop outweighing the costs and below this point it is not theoretically beneficial to use virtual reality. As the hardware and software costs and the modelling time associated with virtual reality fall, however, this point may move (to a position such as line B).

This theoretical model is used to consider the empirical data on virtual reality use across the sector.

Method

A multiple case study method was used to study implementation and use of virtual reality in the lead user firms across the construction sector. Firms were identified through their participation in industry fora on virtual reality, or through virtual reality software suppliers' recommendations. The firms studied operate as architects, real estate owners, housing developers, construction contractors or consultant engineers, and are based in either the USA or the UK.

Data were collected through semi-structured interviews (in 2000/01) and were used in conjunction with supporting company documentation. Wherever possible, interviews were taped and transcribed, and in other cases extensive notes were taken.

In conjunction with this study of users, extensive background data about the use of virtual reality in the construction sector was collected and case studies were conducted with four of the main suppliers (see Table 3),

Table 2 The user companies

	Type of company	Role of interviewee(s)	Location of interview(s)
1	Construction Contractor	• Senior CAD consultant • CAD consultant	UK
2	Construction Contractor	• Head of Integrated Design • Visualization Manager	UK
3	Consultant Engineer and Project Manager	• R&D Engineer (UK) • Project Leader (UK) • Visualization Manager (USA) • Visualization Specialist (USA)	USA & UK
4	Consultant Engineer	• R&D Engineer • IT Manager	UK
5	Consultant Engineer	• Visualization Manager (USA) • Group Supervisor (USA) • Visualization Manager (UK)	USA & UK
6	Major Real Estate Owner	• Head of R&D • Visualization Specialist	USA
7	Housing Developer	• Group CAD Manager	UK
8	Architect	• Head of IT	UK
9	Architect	• Visualization Manager	USA
10	Architect	• CAD Manager	UK
11	Architect	• Partner	USA

Table 3 The supplier companies

	Type of company	Role of interviewee(s)	Location of interview(s)
1	Supplier	• Urban Simulation Manager	USA
2	Specialist supplier	• Sales Manager • Developer	UK
3	Specialist supplier	• Partner	USA
4	Supplier	• CEO	USA

which had technologies specially designed for or tailored to the needs of users in the construction sector.

Though there are limitations to the study, set by the small sample size, a quantitative approach with a statistically significant sample would not shed light on the phenomenon under investigation as there are only small pockets of virtual reality use within the sector. The research method allows major early adopters to be studied in detail. Theoretical sampling was used and decisions regarding what data to collect next were taken during data collection, codification and analysis in order to develop emerging theory. For example, more architects were studied than other organizations, because the findings of the initial case studies were unexpected. Additional cases were studied to ensure that the original cases were not anomalous or unrepresentative of lead users and to deepen understanding of the phenomena observed.

This paper deals with cross-case analysis. Following a brief summary of the results, a theoretical framework will be developed to explore the effect of two aspects of project-based production processes – project size and extent of design reuse – on virtual reality adoption within the sector.

This work has a number of further shortcomings. One is that national differences between the construction sector in the USA and the UK are largely ignored, although location affects firm behaviour. Hence the early adoption of virtual reality in the Los Angeles region, for example, may well be strongly influenced by local film and animation industries. It provides an interpretation of observed adoption of generic technology in construction.

Summary of results

The results provide a snapshot of the rich and varied early uses of virtual reality within the construction sector. Here a broad-brush picture of these data, from construction contractors, consultant engineers and project managers, real-estate owners and developers and architects is given before the paper focuses on wider cross-case patterns.

Construction contractors

The construction contractors studied were both exploring the use of virtual reality on large unique projects, such as out-of-town shopping centres, airports, hospitals and research laboratories.

One of the construction contractors championed the idea of a single project model to manage all of the data relating to a project. This organization had used virtual reality extensively on a number of projects. Identifying errors and clashes early in the process was an important motivation for their use of virtual reality as they could be responsible for rework on site. They had worked closely with academia and now had a close working relationship with a software developer, beta-testing their software.

The other construction contractor had only used virtual reality on one large showcase project but was now looking to implement it more systematically across their organization.

Consultant engineers and project managers

The consultant engineers and project managers studied were using virtual reality on a range of large infrastructure projects, such as airports, rail and road projects.

The first firm invested heavily in visualization technologies. Modellers worked alongside engineering staff for many months on the larger infrastructure projects. Models were used to co-ordinate the design information from a wide range of professionals, to check for clashes and to optimize design. They were then reused for a range of different purposes. Virtual reality is seen as particularly important for value engineering, where costs need to be reduced and decisions need to be made about obtaining value for money without compromising design quality.

The other two firms have a lower use of virtual reality. The second firm had focused on the use of virtual reality for the simulation of rail operations. They had started using virtual reality for highway development and then used what they had learnt to apply the technology to rail development. A model had been built and used by a number of companies involved in the development. The third consultant engineer was using virtual reality on a large collaborative airport project. They were also exploring the use of advanced virtual reality and augmented reality techniques within its research and development and visualization departments.

Real estate owner and developer

The real estate owner studied is a large organization that designs, builds, owns and operates a vast amount of real estate across the globe. They were investing heavily in virtual reality for scheduling construction and hoped to improve the product and reduce waste in the process. By investing capital the company hoped to save on construction costs. They had purchased immersive virtual reality facilities and had full time modellers on the project.

The housing developer studied builds over 2000 houses per year from a range of standard house types. They initially invested in virtual reality for site layout. One of their regional offices became interested in using it at the customer interface. Being able to sell from plan is a major advantage as it reduces the risk of speculative development and the housing developer has used virtual reality to get press coverage and sell from plan.

Architects

A surprising finding of the work was the low use of virtual reality amongst the architectural practices that are seen as lead users by their peers. The four architectural practices studied made little use of virtual reality in the process of designing buildings and infrastructure.

In the first organization, a large commercial practice with some use of interactive 3D, one architect argued that they did not benefit from using it at the customer interface as they wanted to tell their clients a carefully choreographed story.

In the second and third organizations, specialist visualization units had been set up to provide modelling and visualization services internally and to sell their skills externally to clients. One specialist unit had worked for a bank developing a model of its new headquarters in the urban context. The model was used for zoning board approvals and to raise the profile of the development, obtaining television coverage on news bulletins.

In the final architectural practice studied, virtual reality was widely used in the design of media rich and virtual environments. They saw virtual reality opening up new markets for their architectural design skills, as dynamic and spatial media are incorporated into the built environment, and as spaces are designed and represented virtually in interactive, spatial, real-time media. Virtual reality was not being used in the traditional architectural design process and in some instances was used for purposes other than designing physical buildings.

Suppliers

Alongside the case studies with user organizations, two types of suppliers were interviewed: major virtual reality suppliers that identified construction as a key market; and suppliers that developed virtual reality applications exclusively for the sector.

The generic virtual reality suppliers had identified construction as a key sector in the last few years. One had a background in flight simulation and found construction a difficult market. They saw a lot of companies doing really interesting one-off prototypes but failing to fit virtual reality into their business model due to problems with hardware, data interoperability and the amount of time required for modelling. This company had had most success selling virtual reality to planning authorities, as a decision support system for urban planning and it developed an alliance with a GIS supplier. One of its resellers had worked with a UK housebuilder developing models for them to use at the customer interface.

The other generic supplier delivered rendered real-time VR solutions over the Internet, selling to clients in architecture\building, rapid prototyping, automobile, aerospace and manufacturing. They had major clients in the office furniture industry and saw the three main application areas for their tools as marketing\sales, training support and facilities management. They had recently developed a partnership with a CAD supplier.

The specialist suppliers were both new companies that saw a niche in the market. One had been developed out of some university research and sold interactive real-time 3D for design review specifically to the construction sector. The other put more emphasis on simulation and had been set up to produce '4D' models of building and infrastructure.

These suppliers compete, and also collaborate, with established computer-aided design (CAD) and Geographic Information System (GIS) suppliers, which they perceive as 'owning' different parts of the market.

Discussion

This theoretical model fits many of the empirical findings. Leading industrial users of virtual reality are found to be working on large unique projects and/or on many small projects with design reuse. As the theoretical model predicts, on these projects they are able to benefit from the reuse of modelling effort, either by reusing virtual reality on many different activities over the life of the project, or by reusing it across many different projects.

This model also sheds light on the low use of virtual reality by architects. Architects are often involved in small unique projects on which the costs associated with using virtual reality are greater than the benefits. The high risks associated with some of these projects also add to the problems faced. Two of the architectural firms that were identified as lead users of virtual reality were not using it in their own production processes, but were generating libraries of standard forms and selling models to others.

The theoretical model does not, however, directly correspond with the findings and has been modified as shown in Figure 3. Instead of undifferentiated use, virtual reality is being used on large complex projects and on small projects with design reuse and it serves a different purpose on these different types of projects.

On large complex projects, professionals, such as consultant engineers and construction managers, are found to be using virtual reality to visualize and understand engineering problems and hence to reduce risk and uncertainty. Many of these firms are interested in virtual reality as an integrated interface, as advocated by researchers (Aouad *et al.*, 1997a; Issa, 1999). Budgets for hardware and software may be relatively large, functionality is important and there may be a greater investment of time in model building. Models may be returned to over an extended period, as well as being used for integration of different subsystems and design checking, they may be reused for other tasks.

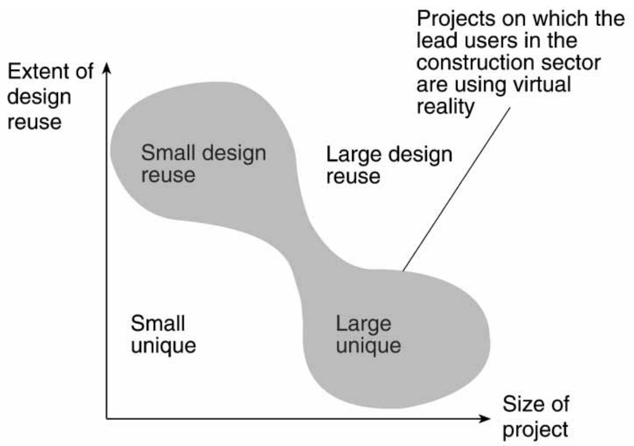

Figure 3 The types of projects on which lead users in the construction sector are using VR

On small projects with design reuse, firms are making a smaller investment, using cheaper web-based systems or outsourcing development. They are gaining benefit from using virtual reality in a more focused manner at the customer interface. Less functionality is required and models of standard parts may be reused across many projects.

These two uses of virtual reality reveal different sets of user requirements. The users of virtual reality on large complex projects emphasize functionality and the integration of data with project-management software through database solutions. The users of virtual reality on small repetitive projects emphasize the ease of model creation and support for the customer interface. The ongoing re-innovation process implies there may be further differentiation and customisation of virtual reality applications for these purposes.

Conclusions

It can be concluded that a single virtual reality application does not have a market in the construction sector. Though virtual reality may be seen as a generic technology, the study revealed distinctly different uses and divergent technological requirements. The process of re-innovation by users may further adapt the technology creating different families of solutions, one placing emphasis on systems integration and another on customer interface.

Implications and further work

The findings suggest that it is not appropriate to implement a single policy towards the promotion of information technologies in construction. Researchers and policy makers need to be sensitive to the use of generic technologies at different levels of aggregation both within the sector and across sectors. They need to be aware that sectors themselves, and the boundaries between them, are changing.

The framework of different types of projects provides a first step towards more differentiated understanding of virtual reality use within the sector. It can be used as a starting point for exploring patterns of use of other generic technologies within this project-based sector and should be tested in future work.

Interaction between design, engineering and construction firms and their IT suppliers also requires further study. It is only if suppliers are receptive that the divergent technological requirements found in this study will lead to the development of different families of technologies through a process of re-innovation.

Further study is also required of the role of intermediary organizations – such as universities and model builders – in adapting technological capacity of the construction sector to the rate of change in the production of generic technologies such as information technology.

References

Alshawi, M. (1995) Integrating CAD and virtual reality in construction, *Conference on VR and Rapid Prototyping in Engineering*, Salford, EPSRC.

Aouad, G., Child, T., Marir, F. and Brandon, P. (1997a) Developing a virtual reality interface for an integrated project database environment, *Proceedings of the IEEE International Conference on Information Visualisation (IV'97)*, London.

Aouad, G., Child, T., Marir, F. and Brandon, P. (1997b) *Open Systems for Construction (OSCON)*, Draft Industrial Report, DOE Funded Project, University of Salford, Salford.

Archibugi, D. (1991) The sectoral structure of innovative activities in Italy: results and methodology, DPhil thesis, SPRU, University of Sussex.

Bouchlaghem, N.M., Liyanage, I.G. and Thorpe, A. (1996) Virtual reality applications in the UK's construction industry, construction on the information highway, *CIB W78 Working Commission on Information Technology in Construction*, Bled, Slovenia.

Fischer, M. and Kunz, J. (1995) The circle: architecture for integrating software. *Journal of Computing in Civil Engineering*, **9**(2), 122–33.

Frampton, R. (2001) *Who Will Buy? An Essay Accompanying a List of 450+ Companies Likely to make a Significant Investment in VR/i3D*, Cyber-Wizard Ltd., London.

Fuchter, K. (1998) Information technology used by Hong Kong contractors, in *The Life Cycle of Construction IT Innovations: Technology Transfer from Research to Practice*. W78, Stockholm, pp. 245–76.

Gann, D.M. (2000) *Building Innovation: Complex Constructs in a Changing World*, Thomas Telford, London.

Gann, D.M. and Salter, A.J. (2000) Innovation in project-based, service-enhanced firms: the construction of complex products and systems. *Research Policy*, **29**, 955–72.

Gardiner, P. and Rothwell, R. (1985) Tough customers: good designs. *Design Studies*, **6**(1), 7–17.

Howard, R., Kiviniemi, A. and Samuelson, O. (1998) Surveys of IT in the construction industry and experience of the IT barometer in Scandanavia. *Electronic Journal of Information Technology in Construction*, **4**, 45, http://www.itcon.org.

Issa, R. (1999) Virtual reality in construction – state of the art report. TG24 Final Report. http://www.bcn.ufl.edu/tg24/final/.

Kalawsky, R.S. (1993) *The Science of Virtual Reality and Virtual Environments: A Technical, Scientific and Engineering Reference on Virtual Environments*. Addison-Wesley, Wokingham.

Kurmann, D., Elte, N. and Engeli, M. (1997) Real-time modeling with architectural space. *Proceedings of CAAD Futures*, Munich, Germany, 809–20.

Laursen, K. and Meliciani, V. (2000) The importance of technology-based intersectoral linkages for market share dynamics, *Weltwirtschaftliches Archiv Review of World Economics*, **136**(4), 702–23.

Malerba, F. (1999) Sectoral systems of innovation and production, DRUID Conference on National Innovation Systems, Industrial Dynamics and Innovation Policy, Rebild.

Mandeville, J., Furness, T., Kawahata, M., Campbell, D., Danset, P., Dahl, A., Dauner, J., Davidson, J., Kandie, K. and Schwartz, P. (1995) GreenSpace: creating a distributed virtual environment for global applications. *Proceedings of IEEE Networked Virtual Reality Workshop*, Boston, MA.

Marquis, D.G. (1988) Anatomy of successful innovations, in *Readings in the Management of Innovation*, M.L. Tushman and W.L., Moore (eds), Ballinger Publishing Company, Boston, pp. 79–87.

Pavitt, K. (1984) Sectoral patterns of technical change: towards a taxonomy and a theory. *Research Policy*, **13**, 343–73.

Retik, A. (1996) Construction project planning: a virtual reality approach, *Proceedings of IPMA '96 World Congress on Project Management*, Paris, France, 597–605.

Riggs, W. and Von Hippel, E. (1994) The impact of scientific and commercial values on the sources of scientific instrument innovation. *Research Policy*, **23**, 459–69.

Rivard, H. (2000) A survey on the impact of information technology on the Canadian architecture, engineering and construction industry, *Electronic Journal of Information Technology in Construction*, **5**, 37. http://www.itcon.org/2000/3.

Rogers, E.M. (1962) *Diffusion of Innovations*, The Free Press, New York.

Rosenberg, N. (1963) Technological change in the machine tool industry, *Journal of Economic History*, **23**, 414–43.

Slaughter, S. (1998) Models of construction innovation, *Journal of Construction Engineering and Management*, **124**(2), 226–31.

Tatum, C.B. (1987) Process of innovation in construction firms, *Journal of Construction Engineering and Management*, **113**(4), 648–63.

United Nations (1994) *International Standard Industrial Classification of all Economic Activities*, ST/ESA/STAT/Ser.M/4/REV.3, E.90.XVII.11.

Von Hippel, E. (1986) Lead users a source of novel product concepts, in *Readings in the Management of Innovation*, W.L. Moore and M.L. Tushman (eds), Ballinger Publishing Company, Boston, pp. 352–66.

Von Hippel, E. (1988) *The Sources of Innovation*, Oxford University Press, Oxford.

Von Tunzelmann, G.N. (2000) Technology generation, technology use and economic growth. *European Review of Economic History*, **4**, 121–46.

Whyte, J. (2002) *Virtual Reality and the Built Environment*, Architectural Press, Oxford.