Forces Driving Adoption of New Information Technologies

By Panagiotis Mitropoulos[1] and C. B. Tatum[2]

Abstract: This paper investigates the forces that drive construction firms to adopt new information technologies. The research focuses on CAD and electronic data interchange technologies and studies in-depth eight innovation adoption decisions. The paper presents the findings regarding the forces that created the managerial stimuli for innovation and the organizational characteristics that played an important role in the adoption. The investigation identified four forces that drive innovation: competitive advantage, process problems, technological opportunity, and institutional requirements. These forces change over time and drive the diffusion of a technology in the industry. The study also found that different organizational characteristics determine a company's sensitivity to each force. The paper proposes a new model of diffusion of new technologies and presents the implications for increasing the rate of innovation in the industry.

INTRODUCTION

Advances in technology are widely regarded as major sources of improvement in the competitive position of firms and industries. However, the benefits from technological advances depend on the extent to which these technologies are utilized. The construction industry is slow in adopting new technologies with negative consequences on productivity and international competitiveness [Business Roundtable 1982; International Trade Administration (ITA) 1984; National Research Council (NRC) 1988]. The need to accelerate the rate of technological innovation in the construction industry has been well identified and documented [D. W. Halpin, unpublished paper presented at the Technology Innovation in Construction Seminar, Zurich, April 1991; Subcommittee on Construction and Building (SCB) 1994].

The goal of this research is to better understand what drives construction firms to adopt new technologies and what factors strongly influence (facilitate or impede) the technological change. Thus, the study focuses on how the need for a new technology emerges and what contextual and organizational factors influence its adoption.

The research investigated eight adoption decisions and focused on two commercially available information technologies, electronic data interchange (EDI) and 3D CAD. The research design was multiple case studies. Each case was analyzed to identify (1) the forces that initiated the change; (2) the factors that managers considered during the decision; and (3) the organizational factors that influenced the decision. Then the cases were compared for similarities and patterns.

The paper first defines the basic concepts and then reviews the literature and presents the case studies. The findings identify four different forces for innovation and the different organizational characteristics that affect a company's sensitivity to each of the four forces. Finally, the paper proposes a model that may explain the diffusion of new technologies and develops recommendations for increasing the rate of innovation.

DEFINITIONS

Innovation is an idea, practice, or material artifact perceived to be new by the relevant unit of adoption (Tornatzky et al. 1983). An innovation can be technological, such as a new product or process technology, or administrative, as in the case of a new structure or administrative system pertaining to organizational members (Damanpour 1991). As regards the nature of technological innovation, several studies distinguish between product and process innovation. In the context of this paper, a process technology is defined as a technology that contractors use to plan, execute, and control construction operations.

Diffusion is the process by which a new technology becomes accepted and used by its potential users. Adoption is the process by which an individual or organization identifies and implements a new technology (Rogers and Shoemaker 1971). Thus, adoption refers to the same process as diffusion but from the perspective of the adopting unit.

A decision process is a set of actions that begin with the identification of a stimulus for actions and ends with the specific commitment to action (Mintzberg et al. 1976).

LITERATURE REVIEW

Diffusion Research

Diffusion research examines the rate of adoption of an innovation through a population of potential users. Cumulative adoption over time is often depicted as an S-curve (based on epidemic models), although there are many exceptions and it is not known when or why the curve applies (Mohr 1987).

A large amount of research has attempted to identify the critical characteristics of a technology that facilitate its adoption (Tornatzky and Klein 1982; Rogers 1983; Wolfe 1994). Rogers (1983) proposed five attributes of a new technology that are related to its adoption:

- "Relative advantage," that is, the degree to which the innovation is perceived as better than the technology it replaces, including technical performance, cost, risk, or other attributes
- "Compatibility" with values, norms, and operations
- "Complexity," that is, the difficulty in understanding and using the technology
- "Observability" and "triability" refer to the ability to observe and test on a limited basis the performance of the new technology

Other researchers emphasized the economic characteristics of the technology (Mansfield 1968), the "radicalness" of the innovation (Dewar and Dutton 1986), the centrality—that is, whether the technology is critical for the organizational performance (Nord and Tucker 1987)—and other characteristics. Although several innovation attributes have been proposed, the research has not identified the managerially important innovation attributes that primarily influence the rate of diffusion (Downs and Mohr 1976; Adler 1989).

[1]Perf. Improvement Coordinator, DPR Construction Inc., Redwood City, CA 94065; formerly, PhD, Civ. Engrg. Dept. Stanford Univ., Stanford, CA 94305-4020.

[2]Prof., Civ. Engrg. Dept., Stanford Univ., Terman Engrg. Ctr. Stanford, CA.

Note. Discussion open until March 1, 2001. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on August 16, 1999. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 126, No. 5, September/October, 2000. ©ASCE, ISSN 0733-9634/00/0005-0340–0348/$8.00 + $.50 per page. Paper No. 21116.

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Organizational Innovativeness Research

The organizational innovativeness research ''stream'' investigates the determinants of an organization's propensity to innovate. According to Rogers (1983), in about 60% of all diffusion research, the dependent variable is innovativeness, which is usually assessed by the timing of adoption of a technology or the number of innovations an organization adopted in a given time period. Innovativeness research has focused on the influence of organizational characteristics including (1) centralization of decision making (Zaltman et al. 1973); (2) technological capabilities (Dewar and Dutton 1986; Cohen and Levinthal 1990); (3) organizational environment that supports innovation (Adler 1989; Burgelman and Rosenbloom 1989); (4) slack resources that enable organizations to search for solutions (March 1981); and (5) external communication channels that increase awareness of innovations (Rogers 1983).

Diffusion research has been criticized for inconsistent findings and lack of explanatory power (Downs and Mohr 1976; Tornatzky and Klein 1982; Mohr 1987; Clark and Staunton 1989). Factors that appear to have strong effect in one study have small, none, or even negative effect in other studies, and no set of characteristics that differentiates more innovative from less innovative organizations has emerged (Tornatzky et al. 1983). Gold (1981) suggested that innovation research should pay more attention to the decision-making process and the market context.

In construction-specific research, Tatum (1989) classified the organizational factors that affect innovation into three groups:

- Organizational structure. A large number of hierarchical levels or high separation of functions impedes the communications among the groups involved in the process.
- Organizational culture. A culture that encourages innovation is characterized by support for champions, freedom of the doer to decide how to proceed with the innovation, commitment of money, and tolerance of risk.
- Key individuals. The ''gatekeeper'' is the individual who identifies external technology. The ''champions'' are the individuals who absorb the risks and drive the change.

Industry Environment

Utterback (1974) argued that a firm's potential for innovation is a function of its environment, including economical, social, and political factors. According to Mowry and Rosenberg (1979), the mechanisms of ''technology push'' and ''market pull'' are both important for the innovation process. Competitive pressures often drive firms to adopt new technologies to differentiate from competitors or to gain a cost advantage (Mansfield 1968; Porter 1985). Studies of new product and process development support the argument that market pull forces are the primary influence on innovation, compared to technology push [Arthur D. Little Inc. (ADLI) 1963; Myers and Marquis 1969; Langrish et al. 1972].

Network research argues that the rate of adoption depends on the interactions between adopters (Coleman et al. 1977; Burt 1987; Valente 1991). Abrahamson (1991) argued that imitation effects play an important role in the diffusion of innovations.

In the construction industry, contractors historically have emphasized the ability to manage labor and subcontractors as the key element in competitive pricing. However, the increased technical complexity of facilities, competitive pressures to owners who demand ''more construction for the money'' (Business Roundtable 1982), and increased international competition are forcing a shift in the basis of competition from managerial to technological issues (Tatum 1988).

Hansen's study (1993) of decisions by four architectural/engineering/construction firms to upgrade their CAD systems concluded the following: (1) The impetus for innovation comes mostly from sources outside the strategic planning process and includes pressures from clients, internal champions, and technological opportunities for increased productivity; (2) slack resources appear to be more important in the adoption decision than in the decision to upgrade the CAD system; (3) there is little formal assessment of risk but more effort to minimize the risks, typically by funding the technology from existing projects; and (4) the existing technological capabilities influence the selection of the system used.

Barriers to Innovation

Tatum (1989) identified technological risk, financial risk, and risk of rejection by workers as important barriers to adoption of new construction technologies, Paulson and Fondahl (1980) identified three major barriers that impede development and implementation of new technologies: (1) Research filters that may prevent further development of an idea, if it is not expected to be cost effective; (2) technical risk that prevents contractors from using ideas that are not fully developed; and (3) technology transfer barriers that prevent the adoption of mature, cost-effective technologies and include lack of awareness about new ideas, problems in communicating how these ideas could be effective, risk and liability involved in trying something new, difficulty in gaining approval from third parties (such as owners, designers, and regulatory authorities), and resistance to change.

Summary and Point of Departure

The review of the literature resulted in the following observations:

- A large body of the literature argues that the diffusion of a new technology depends primarily on the attributes of the technology. However, the research has not identified the technology attributes that mostly influence the rate of diffusion.
- Innovativeness research argues that the innovative behavior of organizations depends on organizational characteristics, but no consistent characteristics have been identified.
- Another body of research argues that the innovative behavior of organizations depends largely on external forces, generally grouped as technology push and market pull.
- The literature does not explain if or how these factors interact to influence the adoption of innovations.

This study uses in-depth case studies to identify what and how external factors and organizational characteristics strongly influence the adoption of new information technologies in construction firms. As a starting point, the data collection and analysis focused on the following factors:

External Factors

- Market pull (including customer demands and competitive pressures)
- Technology push, that is, the opportunity offered by a new technology to improve operations

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Organization Factors

- Top management's attitude toward technology—indicated by the perceived importance of technology for the company's performance
- Organizational culture that values innovation—indicated by the existence of mechanisms, incentives, and resources for the identification and implementation of new technologies
- Technological capabilities related to the new technology
- Slack resources—indicated by the availability of resources that could be used for other than operational expenses

The data was collected through interviews with the decision makers. This enabled better understanding of how (or if at all) the above factors influenced the adoption decision. Furthermore, to assess the importance of these factors in each case, the researchers and the decision makers examined alternative ''what-if'' scenarios to see if the adoption would have still happened if these factors had different value. For example, ''Would the technology have been adopted if the X technical abilities were not available in-house?''

The research also examined how the decision makers addressed the technical and financial risks (which have been identified as important barriers to innovation). The findings related to the decision-making process and the risk-management issues are presented in another paper (Mitropoulos and Tatum 1999).

CASE STUDIES OF TECHNOLOGY ADOPTION DECISIONS

This research studied eight cases of adoption of CAD (five cases) and EDI technologies. The focus on these two technologies was necessary for a feasible research scope while still allowing generalizations of findings across information technologies. In two EDI cases, an EDI system was used in conjunction with an electronic document management (EDM) system.

The study examined three company-level and five project-level decisions in order to identify different possible stimuli for adoption of a new technology. Two more criteria were used for the selection of cases. First, the decisions had to be recent (to avoid problems with memory distortion and postrationalization). Second, more than one key decision maker had to be available for interview. Table 1 summarizes the main characteristics of the adopting organizations, the technologies, and the decisions studied.

The study included three mechanical contractors and two general contractors. The mechanical contractors differ in the type of work they perform (design/build versus construction only) and the market sector (public versus private, low or high tech). From the two general contractors, one operates in the industrial and commercial sectors and one in the heavy/civil sector. All contractors are large companies with an annual volume of work that exceeds \$100,000,000 and with >100 employees.

Case 1: 3D CAD Adoption by Mechanical Contractor

This mechanical contractor operates in the commercial and industrial sectors. More than 80% of the firm's work comes through competitive bidding on plans and specifications. Although the market is growing slowly, the competition remains very high, in part because of many new entrants. The company's culture does not value innovation; being technologically advanced is not considered important for competitiveness and management emphasizes cost reduction and does not encourage employees to innovate.

In June 1993, the firm started evaluating 3D CAD technology. What led to the evaluation of 3D CAD was the increased costs of detailing in recent years, which was a result of the reduced quality of the design drawings. The project managers were so dissatisfied with the increased costs of detailing (an increase of about 100% in the last 5 years, according to the vice president of operations) that the issue was repeatedly discussed at the board of directors. A secondary driver was the increased demands of customers for CAD drawings (either as-builts or coordination drawings). In those cases, the contractor used a specialized subcontractor to develop the CAD drawings.

Case 2: 3D CAD Adoption by Design/Build Mechanical Contractor

The company in this case study is one of the largest mechanical contractors in the Bay Area (San Francisco, Calif.). The company's primary customers are private owners of industrial plants and buildings. The firm specializes in the design, installation, and maintenance of mechanical systems, process piping, plumbing, refrigeration, controls, etc. About 75% of the work is negotiated contracts and about 50% of the projects involve design/build services. The company values new technology and has a reputation for innovation in the industry. According to the owner, advanced technology is essential for competitiveness.

In recent years, the demand for quality of detailing for the

TABLE 1. Summary of Cases

Case (1)	Contractor (2)	Sector (3)	Size (4)	Technology (5)	Decision (6)
1	Mechanical contractor	Industrial Commercial	Volume: \$100,000,000 Employees: 600	3D CAD for detailing and coordination	Adoption of 3D CAD at company level
2	Mechanical contractor	Commercial Hi-tech	Volume: \$120,000,000 Employees: 700	3D CAD for detailing	Adoption of 3D CAD at company level
3	Mechanical contractor	Commercial Hi-tech	Volume: \$250,000,000 Employees: 750	3D CAD for detailing	Adoption on biotech project Later adoption at company level
4	General contractor	Heavy/civil	Volume: \$200,000,000 Employees: 280	3D CAD for construction drawings	Adoption of 3D CAD on hydroelectric project
5	Same	Same	Same	EDM system for communication	Adoption of EDM system on hydroelectric project
6	General contractor	Commercial Hi-tech	Volume: \$600,000,000 Employees: 300	EDM/EDI system and new cost control system	Organizationwide adoption of EDM/EDI system and cost control system
7	General contractor	Heavy/civil	Volume: \$200,000,000 Employees: 280	E-mail for communication with owner	Adoption of EDI on DOT bridge project
8	Same	Same	Same	2D CAD for construction drawings	Adoption of 2D CAD on DOT bridge project

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biotech projects has increased due to (1) the increased complexity of the facilities; and (2) Food and Drug Administration requirements for documentation. Thus, the detailing process is a critical capability for the contractor's success. In this case, the detailing process was not considered a problem, but the company's owner believes that automation of this process is critical for long-term competitiveness. The use of 3D CAD for detailing is part of the vision for automated operations.

Case 3: 3D CAD Adoption by Piping Contractor

The company is a large piping contractor with offices and fabrication facilities across the United States. The contractor specializes in design, installation, and start-up of high-purity piping for semiconductor, biotech, and pharmaceutical facilities. It offers ''turnkey'' (design/build), ''design-assist,'' and construction-only services. Management considers technology essential for the success of the company and tries to ensure that the firm is at the leading edge of high-purity piping technology.

The contractor first used 3D CAD in mid-1991 on a biotech project. The need to communicate the complex facility design to the end-users, and avoid changes and rework during construction, led the contractor and the client to develop a detailed 3D CAD model.

Case 4: 3D CAD Adoption by Heavy/Civil Contractor

The contractor in this case focuses on heavy construction work in the public sector. Customers are primarily public agencies such as federal and state departments of transportation, the Corps of Engineers, the Bureau of Reclamation, etc. The size of projects ranges from $20,000,000 to >$1 billion. Overall, the company values technology. The firm has strong engineering skills, and the project managers have the freedom to select the technologies for their projects. However, management does not commit resources from overhead to innovation. Typically, the resources for implementation of a new technology are allocated from a project budget, which results in a cautious attitude to innovation.

On a recent hydroelectric project, the project manager and the project engineer decided to use 3D CAD for development of lift drawings. The use of CAD was not driven by any problems or by dissatisfaction with the previous method (hand drafting). Because of the availability of the design in 3D CAD and the availability of a 3D CAD system in-house (it was purchased and used on a previous design/build project), the project manager identified the opportunity to use the technology to improve a project process.

Case 5: Adoption of EDI/EDM System by Heavy/Civil Contractor

This case describes the adoption of an EDI/EDM system by the same contractor and project as CASE 4. On the above project, the contractor was planning to use an EDM system with a network for filing, sharing, and communicating project documents in an electronic format. The system had been acquired on a previous project to manage the documentation required for litigation purposes.

The project manager identified the opportunity to use the already available technology and improve the management and communication of project information. With the support of technical staff at the home office, the company identified a configuration of the system based on available software and hardware. Given the low costs of the system, the company saw an opportunity to develop and test the system.

Case 6: Adoption of EDI/EDM System by General Contractor

The organization in this case is a general contractor, construction management, design/build firm that specializes in industrial and institutional buildings. The company has expertise in semiconductor, biopharmaceutical, and food facilities. The size of contracts managed range from $1,500,000 to $600,000,000, and the contractor is typically paid a negotiated fee. The company's top management has a strong positive attitude toward new technology. The contractor's executive vice president is a strong supporter of innovation.

The decision involved the adoption of an organizationwide EDI/EDM system for filing, retrieving, and communicating project information electronically. Competitiveness was the main reason for this decision. For a construction management firm, the ability to collect, organize, control, and distribute project information is a critical capability. Thus, the adoption of the EDM system was considered essential for future competitiveness.

Case 7: Use of E-Mail on Bridge Project

This case describes the adoption of an e-mail system for electronic communication between the contractor and the project owner (a state department of transportation) on a bridge project. The contractor is the same company as in Case 4. Although both organizations had e-mail for internal communication, this was the first project where the contractor and the owner used e-mail for communication with another project party. The project involved the construction of a drawbridge (bascule bridge) parallel to an existing bascule bridge, with a total cost of approximately $200,000,000.

The contractor's project manager and the owner's resident engineer decided to use an e-mail system because it presented an opportunity to improve the payment process and cross-organizational communication.

Case 8: Use of CAD by Heavy/Civil Contractor

This case involves the same contractor and project as Case 7. On this project, the contractor decided to use 2D CAD for lift drawings. This was the first time that this area office used 2D CAD on a project, and also it was the first time the contractor used CAD on this type of bridge project, where the lift drawings were not repetitive. Thus, the case illustrates the use of an existing technology for a new purpose.

The availability of the design files on CAD (DOT had performed the design on CAD and made the CAD files available), the availability of the technology in-house, and the availability of site engineers who were familiar with the technology presented an opportunity to use CAD for construction drawings.

ORGANIZATIONAL AND CONTEXTUAL DETERMINANTS OF INNOVATION

The analysis of each individual case focused on two sets of factors: (1) The driving forces that initiated the adoption process; and (2) the organizational characteristics that influenced the decision to adopt. Then, the across-case analysis compared the cases according to similarities and differences. Table 2 summarizes the driving forces and organizational factors that influenced the adoption in each case.

The results identified four forces that motivate contractors to adopt a new information technology. The analysis also found that different organizational characteristics determine the company's sensitivity to each force. The four major drivers for process innovation are the following:

- Competitive advantage: Cases 2 and 6
- Process problem: Cases 1 and 3

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TABLE 2. Innovation Drivers and Organizational Characteristics in Each Case Study

Case (1)	Driving force(s) (2)	Organizational characteristics (3)
1	Increased detailing costs Owners' requirement for CAD drawings	Top management's reactive attitude toward innovation
2	Automate a critical process to gain competitive advantage	Top management's vision and search for competitive advantage
3	Inability of 2D drawings to communicate complex design	High in-house capabilities Positive attitude toward technology
4	Availability of 3D CAD system and design in 3D	In-house capabilities Existence of champion
5	Availability of EDM system	In-house capabilities Existence of champion
6	Automate critical process to gain competitive advantage	Top management's vision and search for competitive advantage
7	Availability of e-mail system	In-house capabilities Existence of champion
8	Availability of CAD system and capabilities	In-house capabilities Existence of champion

- Technological opportunity: Cases 4, 5, 7, and 8
- External requirements: Secondary driver in Case 1

Competitive Advantage

Cases 2 and 6 illustrate that a strong driver for adoption of new information technology is the managerial goal for competitive advantage (increased ability to win projects). As the two cases show, the potential for competitive advantage exists when (1) the technology improves a critical organizational capability; and (2) most competitors do not use the technology.

In Case 2, 3D CAD was considered essential for the automation of work processes and future growth. In Case 6, the EDM system addressed a critical capability—the general contractor's ability to gather, organize, and communicate project information across project participants. According to senior managers, the competitive advantage is reduced over time. As more competitors adopt the technology, the uniqueness and differentiation that the early adopters had is lost.

Sensitivity to Competitive Advantage

Cases 2 and 6 indicate that the primary organizational factors that make a firm sensitive to the potential competitive advantage are top management's aspirations and proactive attitude toward technology. In both cases, top management emphasized the importance of new technology for competitiveness and the importance of keeping up with the technology rather than the competitors.

Another common characteristic was the approach to risk. In both cases, the new technology involved high initial costs and higher operational costs (at least in the short term). The primary expected payoff was increased differentiation and ability to win contracts, rather than reduced costs. The managers did not establish a method to measure the competitive benefits from the innovation; they perceived it as a critical ability that the company had to have. To manage the risk, the managers in both cases took the following steps: (1) Thoroughly specified the technological capabilities needed; (2) selected the technology that was closest to their needs; and (3) followed an implementation strategy that maximized the probability of success, rather than minimizing the risk. Management hired consultants to modify the system as needed and provide extensive training. Furthermore, management paid personal attention to the first implementation effort and selected a supportive project manager. [For a detailed analysis of the decision-making and implementation process, see Mitropoulos and Tatum (1999)].

The companies in these two cases have two more things in common. First, they operate in the private high-tech sector (semiconductors and biotech facilities) and their clients are manufacturing firms that not only value but ''live by new technology.'' Thus, it is possible that the proactive attitude is a result of the clients' attitude to technology and that the success of these companies is related to the compatibility of the contractor's values with the client's values. Second, both firms adopted the new technologies in a period of high market and company growth. This behavior may suggest that successful companies may be more likely to focus on improving their competitive advantage (success brings success).

Process Problems

In Cases 1 and 3, the adoption was initiated by a problem. A ''problem'' is a mismatch between the required level of performance (cost, schedule, quality, safety, etc.) and the actual performance. In Case 1, the increased costs of detailing led to consideration of 3D CAD. In Case 3, the complexity of the facility was expected to result in rework, increased costs, and delays during construction. These cases illustrate that problems increase over time due to changes in the firm's supply or demand factors:

- In Case 1, a change in a supply factor—the reduced quality of design—resulted in increased and unpredictable detailing costs.
- In Case 3, the increased complexity of high-tech facilities (demand factor) made the previous technology (2D drawings) unable to effectively communicate the design. During data collection the contractors identified several other cases where a new technology was used because of a problem.
- Company growth is another ''demand factor'' that drives technological change in two ways. First, as a company grows, it undertakes larger and more complex projects, with increased requirements. Second, as the volume of work increases, the existing processes often become unable to perform in a cost-efficient or timely manner. For example, one of the contractors had recently adopted a bar-coding system as a response to increased inventory management costs, which were in turn caused by the company growth.

In general, process problems increase over time and increase the pressure to adopt a technology. These pressures may differ for different technologies and industry sectors.

Sensitivity to Process Problems

Cases 1 and 3 illustrate that the company's type of work (e.g., unique projects) and the market conditions are the primary causes of problems, rather than the organizational climate for innovation. Companies with state-of-the-art projects face higher requirements and are often forced to innovate independent of their attitude toward innovation. Internal characteristics also influence the company's perception of and reaction to problems. In Case 1, the increased detailing costs have been a problem for several years, but management decided to take action only when the problem became severe. Thus, management's performance aspirations determine when a problem is ''significant'' enough to require action. In both cases, management estimated the cost of the new technology versus the cost of using the existing method. Case 1 was the

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only case where management measured the financial impact of the new technology (by continuing to track the detailing costs).

During data collection, it was found that contractors often use another strategy to respond to increased project requirements: Negotiate and try to reduce the requirement rather than change their process. For example, when contractors are faced with a new design requirement that increases the costs of the available method, they may request that the designer change the design into one that they are familiar with, rather than use a new method.

Technological Opportunity

This force is the technology push force. In four cases (4, 5, 7, and 8), the technology adoption was solution-driven. What initiated the decision was the identification of the technology and not a particular need or improvement goal. In Case 4, the contractor's designer had used 3D CAD on an earlier project. In Case 5, an EDM system had been used for litigation purposes at the end of a previous project. In Case 7, e-mail had been used for intrafirm communication and, in Case 8, 2D CAD had been used for larger, more repetitive projects. Thus, the technology was already available in-house when a project manager or project engineer saw the opportunity to improve a work process. However, no specific performance goals were set and no quantification of the benefits occurred.

In all four cases, the investment required was low; the software and hardware were already available in-house, and the users required very little or no training. Thus, the adoption was a low cost experiment. According to the decision makers, if the innovations required an investment larger than the slack resources they had under their control, they would have to perform a more serious evaluation of the benefits. Because of the low cost, it was not considered necessary to quantify the savings. The managers did not establish a method to measure the process improvements (in speed or quality) that resulted from the technology. However, the decision makers assessed the cost of failure. In all four cases failure of the technology would not affect the success of the project.

Finally, the cases illustrate that technological opportunity increases over time, as the organizational capabilities increase and the technologies improve in terms of technical and financial feasibility. The following factors were identified to increase the technical and financial feasibility of the technologies in these case studies:

- Increased organizational capabilities. In Cases 4 and 8, the availability of young engineers with exposure to CAD was an important factor that enabled the use of CAD.
- Availability of complementary technologies. Technological changes in other interdependent processes increase the feasibility of a new technology. The availability of design on CAD was a major factor that increased the financial feasibility of CAD in Cases 4 and 8. In Case 8, the use of 11×17 in. drawings enabled the use of printers for CAD drawings (rather than plotters), and printers were already available on site.
- Reduced costs of technology. The reduced costs of 3D CAD in recent years, the development of systems specialized for mechanical contractors, and the ability to download CAD data to fabrication equipment increased the opportunity CAD offered. According to the contractor in Case 6, the increased use of the EDM System in other paper-intensive industries has resulted in improved technology and reduced technical risk.

Sensitivity to Technological Opportunity

The four cases indicate that the organizational factors that determine the company's sensitivity to technological opportunity are (1) existence of champions who identify the potential benefits; (2) slack resources; and (3) existing organizational capabilities.

- The identification of the potential benefits initiated the decision-making process. The managers emphasized time savings, reduction of nonvalue adding activities, learning, and potential benefits on future projects. The managers did not expect significant benefits on the specific project, but they took a long-term perspective, expecting more benefits on future projects.
- The availability of slack resources enabled the organizations to adopt the technology on a limited basis without much need for cost justification. In the studied cases, the costs were low and were covered from the project budget.
- The availability of organizational capabilities reduces the cost of the technology and the slack resources required. Thus, the higher the organizational capabilities, the more probable a company will be to take advantage of a technological opportunity.

In this study, the changes driven by technological opportunity were incremental improvements, rather than radical changes. Significant technological changes were driven by competitive advantage or problems. This may suggest that technological opportunity may not be, in itself, a strong force that can initiate significant technological change.

External Requirements

The fourth driver for adoption of a process technology is external requirements. In this case, the adoption is forced by powerful external actors, such as clients and regulators, who may demand the use of a specific process technology (as opposed to problems, where the clients may have increased product requirements but do not specify the process technology). Failure to adopt the specified technology would result in loss of competitive position (reduced ability to win projects).

External requirements were a secondary driving force in Case 1, where the clients' requirements for CAD drawings had an influence on the decision. All contractors participating in the interviews identified instances where they used a new technology because of clients' requirements. Several contractors stated that clients' demands were the driving force for use of computerized scheduling systems.

The contractors identified three sources of such requirements: clients, competitors, and regulations:

- Clients often specify project control technologies (such as scheduling tools and, in some cases, cost control systems and e-mail).
- Competitors also create pressures for adoption. Several contractors mentioned that they have to maintain ''equal footing'' with the competitors and identified technologies that have become ''industry standard.'' However, all the contractors stated that they would not adopt a new technology simply because competitors use it; the technology would have to give the competitors an advantage.
- Regulatory agencies are another source of external requirements. Although regulations did not influence the use of CAD or EDI, they have driven the use of other technologies (e.g., the Occupational Safety and Health Administration requires the use of safety technologies).

The data from the interviews indicates that external requirements increase over time. The contractors mentioned that most large owners require the use of P3 scheduling software. Also, in recent years more owners require the use of CAD. Also, the state DOT's resident engineer in Case 2 stated that, if the use

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of e-mail was successful, it would become a requirement on future projects. An example of how clients' requirements increase was given by a facility manager of a large pharmaceutical firm. In recent years, the company hired a number of in-house project managers who had previously worked on offshore platform projects, where the use of the P3 scheduling system is a standard. These managers required the contractors and designers to use the P3 scheduling system on their projects.

Sensitivity to External Requirements

Contractors with low technological capabilities and reactive attitude to technology are more sensitive to external requirements, that is, it is more probable to adopt a technology because of external demands. As in the case of process problems, sometimes the contractors try to negotiate the clients' requirements rather than change their method. Also, when such requirements are infrequent, the contractors typically acquire the capabilities needed through subcontracting. This was the strategy that the contractor in Case 1 used before the in-house adoption of 3D CAD—when an owner required CAD as-builts, the contractor would hire another firm to develop the CAD drawings. In terms of diffusion, this strategy shows that a technology may be used in the industry, but without being adopted in-house by contractors.

IMPLICATIONS FOR RESEARCH

This research extends the existing innovation literature in the following ways:

- The findings indicate that the rate of diffusion of a process technology is a function of the four forces, rather than the technology characteristics.
- The findings indicate that innovative behavior is driven primarily by industry conditions (the four forces) and secondarily by organizational factors (sensitivity to the forces).

Rate of Diffusion

The paper proposes that the rate of diffusion of a technology depends on the four identified forces. Fig. 1 illustrates that the (assumed) S-curve of diffusion is a result of the sum of the four forces. The model provides the following hypotheses for future testing:

- At the early stages of the technology diffusion, the primary reasons for adoption are competitive advantage or an important process problem.
- Technological opportunity is low at the early phases, as the costs of the technology may be high and the required skills may not be available. At the early phases, the costs of the technology may be higher than the savings (thus the force has a negative value).
- Process problems are assumed to increase over time as companies grow, project characteristics change, and performance requirements increase.
- External requirements typically do not exist in the early phases but increase later as more competitors use the technology and customers require its use.

The strength of these forces varies for different technologies and industry sectors. For example, 3D CAD may be a core technology for mechanical contractors, as it addresses a core process (detailing), but not for a construction management firm. Also, different sectors are subject to different growth,

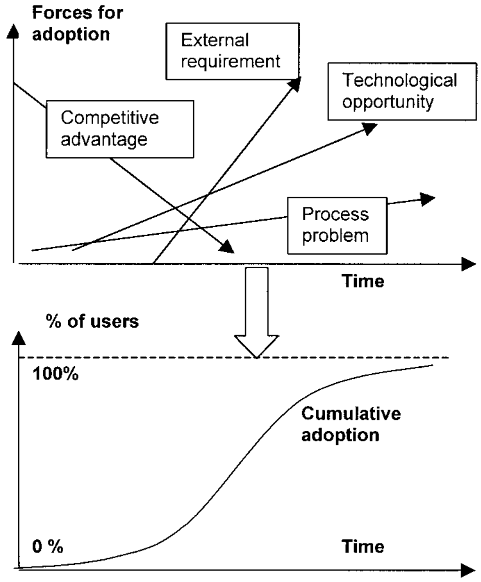

FIG. 1. Innovation Drivers and Technology Diffusion

TABLE 3. Factors Affecting Technology Adoption Forces

Force (1)	Factors affecting strength of force (2)	Trend over time (3)
Competitive advantage	Core technology Adoption by competitors	Decrease
Process problems	Supply factors (sector) Demand factors (sector) Sector growth	Increase
Technological opportunity	Technology costs Availability of skills Availability of complementary technologies	Increase
External requirements	Owner's demands (sector) Regulations (sector) Use by competitors (sector)	Increase

project characteristics, and owners' or regulatory demands. Table 3 lists the industry factors that affect the adoption forces.

For example, the following conditions and trends create pressures for use of 3D CAD on mechanical contractors operating in the high-tech sectors.

- 3D CAD addresses a core process—detailing (potential for competitive advantage)
- Reduced quality of design increased detailing costs in recent years (created a "problem")
- Increased complexity of high-tech facilities—previous technology cannot meet requirements efficiently (created a "problem")
- Reduced costs of 3D CAD systems (increased technological opportunity)
- More young engineers have the skills to use CAD and, thus, less training costs (increased technological opportunity)
- Availability of complementary technologies (e.g., plotters for CAD) are available because of scheduling demands (increased technological opportunity)
- Lack of industry standards for high-purity piping and, thus, lack of component libraries in CAD (reduced technological opportunity)
- Increasing demands from high-tech owners for 3D CAD drawings (increased external requirements)

Future research is needed to validate the proposed model, with the focus on specific technologies and sectors.

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Innovative Behavior

This research shows that the innovative behavior of organizations may be driven by different reasons (forces). Furthermore, different organizational characteristics determine the sensitivity to these forces. Thus, organizations with different characteristics may behave in a similar way but for different reasons. The findings show that the diffusion of a technology is a complex, dynamic process influenced by several interacting industry conditions and organizational characteristics. These findings may provide some explanation for the inconsistent findings of previous research on organizational innovativeness.

Limitations

The scope of this paper was to present the critical external and organizational factors that influenced the adoption of the technologies. Some of the identified factors may operate as facilitators or barriers to innovation; e.g., if the organizational characteristics reduce sensitivity to the driving forces, they become barriers to innovation. However, other barriers may exist that were not present in these case studies—if other forces existed, maybe the technologies would not have been adopted. One limitation is that the research examined cases of adoption. A study of cases of rejection may reveal other strong internal forces that operate as barriers.

Finally, the study does not provide evidence regarding the factors affecting the success of implementation. To avoid problems of postjustification, the researchers intentionally selected cases where the implementation had not or had just started—however, the study looked into actions that managers took to increase the probability of success. These findings are presented in Mitropoulos and Tatum (1999).

IMPLICATIONS FOR PRACTICE

The findings indicate that the rate of adoption of new technologies will increase if the strength of the four forces increases and/or the organizational sensitivity to these forces increases. Based on the research findings as well as managerial suggestions collected during the research, the following possible actions are identified:

Increase external requirements. Customers can mandate the use of specific technologies. However, many customers do not have good knowledge of the construction operations and the available technologies.

Create ''problems.'' When measuring the performance of work processes, one can identify ''problem areas'' and initiate change. Some managers mentioned that one strategy for innovation is to set high performance goals, thus creating artificial ''problems.'' According to the managers, such goals can effectively mobilize the organization before an external problem initiates change.

Increase potential for competitive advantage. Construction customers can increase the potential for competitive advantage if they consider the contractors' technological capabilities as a criterion in selection. At the organizational level, top management must identify the critical capabilities required for competitiveness, identify the key technologies related to these operations, and monitor the technological developments.

Increase technological opportunity. When the use of a technology is not dictated by a customer, a problem, or a competitive goal, the main factors affecting the adoption are the understanding of the benefits, the availability of resources, and the organizational capabilities. At the organizational level, management must establish mechanisms to identify and test new technologies and provide slack resources for experimentation.

At the industry level, closer cooperation between technology developers and contractors is needed to develop technologies that address the contractors' operational needs. In the case of 3D CAD, the technology lacked features essential for the contractors. Finally, construction customers can reduce the contractors' initial cost and cost of failure by sharing the costs, risks, and benefits of new technologies.

CONCLUSIONS

This paper identified four forces that drive construction companies to adopt new information technologies and the organizational characteristics that affect the sensitivity to these forces. The research provides a better understanding of the innovation mechanisms by illustrating how industry factors, technological factors, and organizational characteristics interact and influence the adoption of new technologies. Finally, the study provides a new model for explaining the rate of diffusion in the industry.

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