Potential Mechanisms for Construction Innovation

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Abstract: Construction presents important opportunities for innovation. Current competitive conditions and owner demands for cost effectiveness provide strong incentives. Examining mechanisms for innovation rather than barriers to technical progress is one means to stimulate advance. This paper describes several advantages and disadvantages which the construction industry presents for innovation. The advantages include project organization, necessity and challenge, engineering and construction integration, low capital investment, capability and experience of key personnel, process emphasis, and variation in methods. Major disadvantages for construction include investment reluctance, competitive conditions, institutional framework, seasonal and economic cyclicity, and the role of suppliers. Based on these conditions, a set of hypotheses is developed (project demands, individual initiative, construction input to design, and transfer from other industries) concerning possible mechanisms for innovation in construction. The paper also reviews prior research regarding innovation in construction and manufacturing, develops practical applications of mechanisms for construction innovation, and highlights conclusions regarding opportunities for technological progress in construction.

Introduction

A strong construction industry with an advancing technological base is necessary for a healthy U.S. economy. It is also important for the solution of current problems with manufacturing and process industries, infrastructure, and mass transportation. The U.S. construction industry has performed poorly in relation to other countries, but there are some examples of innovation. Technological progress differs by segment of the construction industry. In contrast to prior studies of barriers to technical progress in construction, the research described in this paper focuses on identifying mechamisms for construction innovation. Understanding the conditions and actions that have fostered specific advances should help to increase the rate of advancement for the overall industry.

The purpose of this paper is to: (1) Review background knowledge regarding processes of innovation; (2) propose possible advantages and disadvantages of construction for innovation; (3) identify possible mechanisms of innovation in construction; and (4) describe research needed to increase the rate of technological advancement in the U.S. construction industry.

First, prior investigations of innovation in construction are reviewed. Secondly, background research concerning innovation processes is described and findings regarding influences on innovation are reviewed. This background from other industries is then compared with conditions in construction. Next, hypotheses concerning possible mechanisms of

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innovation for construction are developed, research needs are identified, practical applications described, and conclusions highlighted.

Innovation in Construction

The economic implications of technology and the process of technical advancement have interested researchers from several fields. We will first review major contributions to current knowledge of innovation processes in construction. As there is little written directly on this subject, related literature from the fields of construction engineering, economics, and management will be included as well. This review combines the background from these areas using three main groupings: innovation in construction, mechanisms of technical progress, and influences on innovation.

Several definitions provide a useful common understanding for this review. Susskind (53, p. 1) defined technology as "man's efforts to satisfy his material wants by working on physical objects." Construction technology is "the state of the art in construction methods, construction processes, construction equipment, and materials of construction" (8, p. iv). Invention is the process of discovering or creating a new idea; innovation is the first use of an idea by a new unit of adoption (47).

The Business Roundtable's (BRT) study team for construction technology concluded that effective technological advancement is essential to enable the U.S. construction industry to compete with foreign firms, that fragmentation in construction makes innovation more difficult than in other industries, and that technological progress requires owner/user leadership (8). This study also found that managers require that return on investments in construction R&D be at least as attractive as other potential projects, that technology transfer is a greater problem than technology invention in construction, and that effective U.S. construction technological advancement is possible with sufficient incentive and motivational forces (7,55).

The construction literature includes both empirical studies of innovation in specific industry segments (e.g., civil, building, industrial) and findings over all segments. To illustrate the types of prior studies, we will first review them by segment. In addition, the investigations of innovation in other fields (reviewed in the second part of this section) also provide an important background for investigation of construction innovation.

Innovation in Heavy Civil and Transportation Construction.—A series of investigations by Paulson considered technological advancement in transportation construction (39–41). Representative examples of innovation identified in this research include: slurry shield and earth pressure balance tunneling, reverse station construction, and advanced means of underground mining for stations in soft ground (41). This study also found that industry fragmentation, a custom and incentive orientation, and a focus on practical and project matters inhibited technical progress in U.S. transportation construction (39).

Reviews of progress in heavy civil construction identify several types of innovation. Examples include: (1) Advances in concrete materials (20) and concrete construction techniques (62); (2) increased capability of construction equipment (22,26); and (3) advanced techniques used in reclamation construction (5,6). Results of specific tunneling projects (17) indicate successful results based on impressive technical advances by Japanese contractors.

Building Construction.—An NSF-sponsored study investigated the patterns and problems of innovation in five U.S. industries (38). In analyzing building construction, the researchers considered management and organization, materials and components, power tools, mechanical equipment, and prefabrication. The findings indicated no technical changes of major economic significance and identified fragmentation as a major problem restraining technological advancement in building construction.

In contrast, more recent studies found examples of progress in building construction. The Business Roundtable's technology study team concluded that favorable contracting techniques, high levels of designer/constructor interaction, and the use of performance specifications resulted in significant technical advances for commercial projects (7). Japanese use of robotics (18) on building projects illustrates a start for automation. Ventre's investigation of innovation in residential construction (60) used 14 construction advances as a measure of the state of the art. He concluded that adoption has been at least as rapid as for equally significant innovations in other industries. The diversity, dispersion, detachment, and discontinuity of the construction industry, in his view, resulted in a failure to recognize these advances. He also concluded that marketing concerns and fears of consumer rejection motivate deliberate concealment of changes in building construction technology. Quigley found several examples of innovation in building construction and attributed them primarily to R&D activities by suppliers or goverment (43).

Industrial and Power Construction.—The Business Roundtable's technology study team found little technical advance in industrial construction (7,55). They concluded that material suppliers and specialty contractors produced this limited progress. However, innovative equipment and construction methods developed to meet the challenge of individual nuclear projects (52–54) indicate progress in response to specific requirements.

Findings over All Segments.—This background indicates differences between the innovation performance of three major segments in the construction industry. It also suggests that certain factors, present in segments with greater innovation and absent in others, may promote technological progress. These factors provide a starting point for hypotheses concerning mechanisms for innovation in construction. A later section of this paper develops these hypotheses. First, investigations of technical progress in other industries also provide an important background for investigation of construction innovation.

Mechanisms of Technical Progress

Rosenberg (46) identified two key forms of technical progress. The first type focuses on cost reduction by obtaining a greater volume of output for a given input. New knowledge which allows the production of qualitatively superior output from a given resource provides the second type. Another important distinction concerns product and process innova-

J. Constr. Eng. Manage., 1986, 112(2): 178-191

tions. Process innovations generally involve new production methods or new machinery. These capital goods may produce existing products more efficiently or may be required for new products. Product innovations bring new manufactured goods to consumers.

Processes of Innovation.—At the macro level, researchers have viewed technical progress in two opposing ways: as a discontinuous series of major breaks or revolutions (24,50) or as a continuous stream of change (58). Studies of advances in specific industries, such as railroads (10), synthetic fibers (15) and petroleum refining (9), supported the latter view and assigned a greater importance to the cumulative effects of minor changes than to major discoveries.

Two other viewpoints pose a different way of analyzing processes of innovation. The first contrasts the role of technical advances and market forces. The "technology-push" hypothesis suggests that the pace of scientific advance and the size of the research staff determine the level of innovation (21). "Demand-pull" views emphasize the role of need, as indicated by market demand, in producing innovations. Several empirical studies have supported the importance of market opportunity (11,12,16,25,33,49,59). However, Mowery and Rosenberg (35) reviewed these studies and concluded that they did not substantiate the primacy of market demand forces in the innovation process.

Still another way of analyzing processes of innovation concerns the sequence of fundamental scientific discovery and technological advancement. One view emphasizes an early and increasing dependence of technology on science (36). Other researchers concluded that technology builds upon itself (4) and found that empiricism and trial-and-error approaches were important in advancing both technology and science (32). Technical innovations, in this view, force scientific investigation to explain the phenomena involved.

Meyers and Marquis (33) discerned three types of innovations: (1) Complex systems involving many elements, such as communications networks; (2) radical breakthroughs in technology which change the character of an industry, such as the jet engine; and (3) "nuts and bolts" innovations which take place within the firm. Abernathy and Utterback (1) identified the development of a "dominant product design" as a key point in the innovation process. Examples such as the DC-3 aircraft and the Model T automobile illustrate this point of transition from emphasis on product to process innovation.

Rate of Technological Advancement.—Several investigators have identified delay between invention and innovation or diffusion. Lynn's (27) study of 20 advances found a range of 14–37 yrs between innovation and commercialization. For 46 new products or processes in several industries, Enos (9) found an average interval of nearly 13 yrs between invention and innovation. The TRACES II (13) study of 10 innovations found an average duration of 19 yrs between conception and realization.

Influences on Innovation

Market Structure, Firm Size, and Stage of Development.—Researchers considering the microeconomics of technology have investigated relationships between level of innovation and resources devoted, market structure, competition, and profit (21). Schumpeter hypothesized that greater innovation performance of larger firms with greater monopoly power would result from the increasing cost of major innovation (50). He reasoned that advantages for larger firms resulted from extending market power to new products, the availabiility of internal financing, and hiring more innovative people. Mansfield (31) found a varying relationship between the size of the firm and its innovative output in the coal, petroleum, steel, and pharmaceutical industries. Other research indicated that smaller laboratories produce more inventions (19) and that the autonomy and entrepreneurship resulting from decentralizing large firms into small groups promotes innovation (42).

Abernathy and Utterback concluded that a firm's capacity for and methods of innovation depend on its stage of evolution; this ranges from a small technology-based enterprise to a high-volume producer (1). They identified three patterns of firms (fluid, transitional and specific) and found that the rate of product innovation declines as firms progress through these patterns. Process innovation increases in moving to the transitional pattern, and declines thereafter. Madique and Hayes (29) identified a paradox in managing high-technology firms: a need for stability and conservatism contrasted with rapid and sometimes precipitous change. They suggested that managing differently at different times in the evolutionary cycle of the firm, by varying from continuity to reorientation, may be most effective.

Product and Market Characteristics.—Several researchers have attempted to differentiate successful and unsuccessful innovations. As reviewed by Madique and Zirger (30) these investigations consisted of exploratory case studies (34), groups of cases (28), and large surveys (8,33,47,48). The results identified several characteristics favoring successful innovation: (1) Attention to user needs and marketing (3,47); (2) product uniqueness, marketing knowledge, and technical and production synergy (8,30); and (3) in-depth understanding of customers and the marketplace, high rate of growth in markets, management support, and use of existing strengths of the developing business unit (30).

Product and Manufacturing Process Relationships.—Abernathy et al. (2) found that pressures for least-cost production and resulting investment in an efficient but inflexible manufacturing plant thwart process and product innovation. Technological advancement makes existing capital equipment obsolete. Current managerial incentives result in a reliance on external firms to develop advanced process technology. This ignores the potential for user-initiated innovations, a source von Hippel identified as very important (61).

Champions and Entrepreneurs.—The SAPPHO studies (3,47) identified four key roles in successful innovations: (1) Technical innovator; (2) business innovator; (3) product champion; and (4) chief executive. The business innovator, or individual responsible for the "overall progress" of the project, emerged as a principal factor in successful innovation. Madique (28) proposed a relationship between entrepreneurial roles for new products and the stage of organizational development within the firm. Rubenstein et al. found that individuals make R&D projects successful (48).

Several researchers have identified organizational (4,44,57) and behavioral influences on innovation. Peters and Waterman (42) note five conditions within firms which result in "championing systems" and create successful innovations: (1) Expecting failure of a large portion of new product initiatives; (2) providing unstructured support for champions in a "skunk works" environment; (3) separating the organization into "suboptimal divisions" which can focus on specific product development tasks; (4) encouraging internal competition; and (5) fostering intense communication.

Management Priorities.—Hayes and Wheelwright (14) cite several restraints to innovation in the U.S.: profit center forms of organization, emphasis on short term performance, and attention to corporate portfolio management rather than core technologies. The rise of the "marketing concept," which emphasizes consumer desires and market-pull product development, accompanied these conditions. The result is a dominance of imitative, as contrasted with innovative, product designs. Hayes and Wheelwright suggest that overemphasizing the marketing concept "implies opting for customer satisfaction and lower risk in the short run at the expense of superior products and market penetration in the long run" (Ref. 14, p. 18). Parker (37) suggested that innovation is management-intensive and generally involves a high market risk.

Summary of Relation to Current Knowledge

The current empirical knowledge of construction innovation includes specific studies of highway and building construction, supplemented by reviews of technical advancement in other segments of the industry. This background does not include attempts to develop a model of innovation in construction from the limited empirical data.

In contrast, researchers in economics and management have conducted extensive investigations of innovation in manufacturing industries. Their findings include several models of processes for innovation. Although development of a comprehensive theory of innovation remains an important research task, the existing models have assisted in increasing fundamental understanding, focusing management attention on key activities, and setting national policies to increase innovation.

The limited investigation of construction innovation and the demonstrated benefits of similar work in manufacturing indicate excellent opportunity and potential for research on innovation in construction. The increased understanding of fundamental mechanisms for construction innovation expected from this investigation will contribute to essential advancement and increase international competitiveness in this vital industry. Contrasting construction with other industries is necessary before examining potential mechanisms for innovation in construction. Considering the findings of prior innovation research, construction's differences include both advantages and disadvantages for innovation. Although additional investigation is necessary to determine the extent and the influence of these differences, they suggest hypotheses for investigation of potential mechanisms for innovation in construction.

J. Constr. Eng. Manage., 1986, 112(2): 178-191

Construction Innovation Advantages

Compared with manufacturing, the construction industry presents important advantages for innovation. These advantages include several elements which researchers have found to encourage innovation in other industries.

Project Organization.—Construction is structured by individual projects. Each requires creating and disbanding a separate team. This should offer the same advantages of autonomy as the "skunk work" organizations advocated by investigators of innovation in industrial organizations.

Necessity and Challenge.—The individual projects in construction present high levels of necessity and challenge for results. Each includes a unique situation and requirements. This could promote innovation by forcing examination of new technologies for each new and challenging project.

Engineering and Construction Integration.—When project organization provides for engineering and construction integration, through the early assignment of experienced personnel, the consideration of construction experience during the design of the facility can simplify construction process requirements and decrease cost. This allows a high user involvement in process design, as suggested by prior innovation research.

Low Capital Investment.—Construction firms typically involve relatively low capital investment, which allows high flexibility for the adoption of new technologies. In construction firms with high investment, such as heavy civil contractors, technological advancements can result from small incremental investments. For example, the addition of automated control to existing grading equipment has greatly improved productivity and quality.

Capability and Experience of Personnel.—Most construction companies include a pool of technologically experienced personnel. These superintendents and engineers can provide a depth of knowledge concerning the subtle methods required for productive field operations.

Process Emphasis.—The nature of construction, with strong emphasis on process rather than hardware, limits barriers to imitation. New process elements of technologies can spread rapidly without patent restraints. This allows adoption and incremental improvement. It may also discourage innovation.

Variation in Methods.—The work operations of construction present inherent flexibility for improvement. Production processes do not create rigid restraints, as in manufacturing. In fact, the unique elements of each project require the use of differing methods for many operations. These differences offer the opportunity to improve past methods.

Construction Innovation Disadvantages

Despite these potential advantages, several elements of construction have restrained innovation. These characteristics of the industry, individual firms, and specific construction projects each work against technical progress. Much of the prior investigation of innovation in construction has emphasized these barriers.

Investment Reluctance.—The low capital intensity of the industry limits its interest in investment for automation. If a new technology appears to lessen flexibility for work on several types of projects, construction managers resist this possible advance because of the potential restraints. High levels of competition in the U.S. construction industry limit profits available for investment in advanced technology. In addition, the inability to protect advances in the construction process with patents may discourage investment.

Competitive Conditions.—In both geographic regions and specialty segments of the construction industry, competitive conditions may limit willingness to take the technical and financial risks associated with new construction technologies. If a firm is maintaining an adequate share of a market (regional or by specialty operation), then pressures to take the risks of innovation are reduced.

Institutional Framework.—The institutional framework of construction is often cited as a barrier to innovation. This framework includes the large number of construction firms, the contractual and legal background, the treatment of risk and liability, the regulatory influences, and the organization of labor. Each of these factors argues for a static approach to technology.

The fragmentation of the industry, with a large number of firms specialized both by geographic region of operation and by type of construction, limits the resources available to individual firms for innovation. The legal framework of the industry, with an increasing concern for limitation of liability, provides strong incentives for technological inertia. Increasing regulatory requirements, particularly those for safety and environmental protection, divert capital potentially available for new technologies, and encourage proven methods. Uncertain craft jurisdiction complicates the introduction of new methods or equipment.

Tradition strongly influences many construction organizations. Managers, estimators, engineers, and superintendents each see many incentives to repeat methods which proved successful on past projects. This results in a limited acceptance of "champions" for innovations and a fear of risk and liability. It also creates a means orientation of specific methods for specific operations which can prove very difficult to break.

Seasonal and Economic Cyclicity.—A high variation of work volume in the construction industry restrains capital investment and limits economies of scale. This creates a reluctance to make commitments which limit flexibility to respond to seasonal or economic changes in markets.

Role of Suppliers.—With some exceptions, U.S. suppliers to the construction industry have not created the technological advancement that their counterparts have made in other industries. Uncertain market conditions foster a reluctance to invest in further advancements to the equipment and tools used by construction.

These potentials and restraints indicate that elements of the U.S. construction industry correspond with conditions found to promote innovation in other industries. Many companies and projects are innovative. Despite this, the use of consistent technology for many operations and a decreasing U.S. share of world markets indicate the necessity for increased technological advancement. The levels of technological progress in other countries, and the advantages resulting from the advanced technologies, may make technology a key basis for competition in important future construction markets.

Possible Mechanisms of Innovation in Construction

Findings from investigations of innovation in other industries, compared with conditions in the construction industry, suggest possible processes for innovation. Descriptions of innovative projects or advancing construction technologies also indicate several potential mechanisms. In addition, the construction innovation advantages suggest possible mechanisms. These factors provide initial hypotheses for future investigation of innovation in construction.

Needs for Investigation of Construction Innovation

The opportunity and necessity for the advancement of construction technology present a strong need for research to assist industry efforts. The purpose of this research is to increase the fundamental understanding of construction technology and provide mechanisms and strategies for its advancement. Three topics form a possible sequence of investigation: (1) Developing a technological classification of construction operations; (2) exploring the fundamental mechanisms of innovation in construction; and (3) identifying long-term strategies for construction technological advancement.

Technological Structure of Construction Operations.—The fragmentation of projects into separate phases and pieces, uncertainty in weather and other environmental factors, and changes in design requirements all make construction quite different from manufacturing. Though not fully understood, these differences increase both the challenges and the potential benefits of advanced technology. The first phase of this research involves developing a technological classification scheme or taxonomy for different construction operations. Identifying the resources, methods, and tasks which make up construction technology, this classification will provide a measurement tool and means to identify opportunities for technological advancement.

Innovation Processes in Construction.—Many well-recognized barriers in the institutional setting of construction operate against technical change. Despite these, notable successes do occur. The second phase of this research will be to identify and then investigate these innovations, in order to determine the mechanisms which fostered them. The processes of research, development, demonstration, evaluation, and diffusion of new construction technologies will be studied to identify the conditions, decision processes, and management actions which lead to advances in construction technology.

Long-Term Strategies for Construction Technological Advancement.—The third phase will involve developing long-term strategies for technological advancement in construction, based on the classification system and the understanding of mechanisms for construction innovation. These strategies will include ways to recognize opportunities, focus

J. Constr. Eng. Manage., 1986, 112(2): 178-191

research activities, foster competitive advantages from advanced construction technology, and effectively implement those changes with the greatest leverage for advancement. This understanding of the strategic options for, and potential economic benefits of, technological advancement will provide substantial new incentives for innovation and technologically based competition in the construction industry.

Taken as a whole, these three research thrusts complement and mutually reinforce one another. The aggregate program will assist in initiating programmed, systematic, and more rapid technological advancement in construction. This change is essential for improved construction performance and increased international competitiveness of capital intensive U.S. industry.

Practical Applications

The potential results of this research present several opportunities for practical application to accelerate the rate of technological advancement in construction.

At the national policy and overall industry levels, the findings regarding mechanisms for innovation in construction and strategies can provide insight to foster an improved climate for technological advancement. Possible actions include changes in contracting approaches, such as the use of alternatives in bidding, incentives for additional research and development, and assistance in technology transfer.

At the level of the construction firm, the understanding of mechanisms for technological advance could indicate several specific actions. If project necessity proves to be an important mechanism for innovation, managers can emphasize project differences and require the detailed evaluation of alternative methods during project planning. General managers in construction firms of all sizes can encourage "champions" of construction innovation. Possible actions include diversity of experience in career paths, opportunity for interaction with other firms both within and outside construction, and tolerance of mistakes.

On specific construction projects, the consideration of mechanisms for innovation can strongly influence both the planning and direction of operations. Managers can emphasize the necessity and challenge of project requirements, and even magnify these demands in establishing performance requirements. An appropriate project environment can further emphasize the climate for champions of specific innovation.

Conclusion

Technological advancement is an important means for the construction industry to meet challenges of increased cost-effectiveness and improved international competitiveness. A progressive construction industry can assist in solving national problems with manufacturing and process industries, infrastructure, and mass transportation.

Prior investigations of innovation in construction have emphasized the barriers created by the industry's institutional framework. Fragmentation, regulation and labor provide excuses for inertia. Despite this, some segments of the industry have advanced construction technology. Stud-

J. Constr. Eng. Manage., 1986, 112(2): 178-191

ies of heavy civil, transportation and building construction indicate progress. Specific examples from power construction describe innovations in response to challenges presented by individual projects.

Investigators of innovation in manufacturing have identified both mechanisms of technical progress and influences on innovation which may apply to construction. Contrasting views regarding the processes of innovation include: (1) Discontinuous series of major breaks or a continuous stream of change; (2) "technology push" versus "demand pull" as major change forces; and (3) scientific discovery preceding technological innovation or following advanced applications. Possible major influences on innovation identified in the manufacturing research include: (1) Market structure, firm size, and stage of development; (2) product and market characteristics; (3) product and manufacturing process relationships; (4) champions and entrepreneurs; and (4) management priorities. Each of these mechanisms and influences presents opportunities for investigation in construction.

Considering the findings of this prior research, the construction industry presents both advantages and disadvantages for innovation. Any of these form hypotheses for future investigation of construction innovation. The advantages include project organization, necessity and challenge, engineering and construction integration, low capital investment, capability and experience of personnel, process emphasis, and variation in methods. Among the disadvantages in construction for innovation are investment reluctance, institutional framework, seasonal and economic cyclicity, and the role of suppliers.

Each of the advantages results in a hypothesis for possible important mechanisms of innovation in construction. Conversely, the avoidance of any of the disadvantages noted could prove critical in fostering construction innovation.

This background suggests three steps in a research plan to increase understanding of how innovation takes place in construction and provide strategies for programmed, systematic, and more rapid technological advancement. First, we need to develop a framework for classification of the technological structure in construction. This will provide a measurement tool. The next step is evaluating potential mechanisms for innovation in construction. The hypotheses developed in this paper provide a starting point. Empirical data regarding several types of construction innovations are necessary to test and refine these hypotheses. Finally, we need to define research and business strategies to increase technological advancement in construction firms.

The potential applications of this research include national policy-making and increasing innovation in construction firms and on specific projects. Changes in contracting approaches and incentives for R&D investment are possible applications at the national level. Organizational climates which foster innovation and create necessity through certain types of project demands may prove to be important applications at the level of the firm and the project.

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J. Constr. Eng. Manage., 1986, 112(2): 178-191