Innovation in Construction Equipment and Its Flow into the Construction Industry

By David Arditi,[1] Member, ASCE, Serdar Kale,[2] and Martino Tangkar[3]

Abstract: The rate of innovation in construction equipment is measured by using two variables over a 30-year period, 1962–92: The number of new models introduced every year and the technological life of eight earthmoving equipments are considered in this study. The findings indicate that the rate of innovation in the construction equipment industry increased in the 30-year study period. The findings also suggest that these innovations are incremental in nature, stimulated by technological advances in other industries, but primarily driven by market forces. Technological advances are not confined to the industry that produces innovations. The mapping of the interindustry flow of innovations highlights that while construction companies play a predominant role in generating their own technological innovations, they are also heavily dependent on other industries, such as the construction equipment industry for the flow of technical system innovations. As such, the continuous and incremental innovations in the construction equipment industry are bound to act as a catalyst for the generation of technological advances in the construction industry.

INTRODUCTION

The issues associated with the rate of innovation in particular industries and the flow of innovations among industries have attracted considerable attention in the literature (Archibugi et al. 1991; Robson et al. 1988; Pavitt 1984). These studies reveal that the rate of innovation in an industry is dependent on many interrelated factors, and that the rate of innovation in some sectors plays a significant role in the production of innovations used by other sectors (Scherer 1984; Pavitt 1984). For example, innovations in the construction equipment industry are stimulated by environmental dynamics that are characterized by interactions between strategic decisions, marketing policies, production practices, regulations imposed by the government, and research and development (R&D) priorities (Coombs et al. 1989). On the other hand, the construction equipment industry feeds the construction industry, and can be considered the originator of some innovations used in the latter. As a result, some of the benefits of the innovations originating in the equipment manufacturing industry are captured by the construction industry, since increased productivity, safety, cost-efficiency, and new construction technologies depend partly on the use of more advanced equipment.

The research presented here focused on investigation of the rate and nature of the flow of innovations originating in the construction equipment industry and directly impacting the construction industry, based on selected heavy equipment studied over the last 30 years.

CONSTRUCTION EQUIPMENT INDUSTRY

The construction equipment industry is known as a "mature industry" (Hambrick 1983), which refers to an industry that passed from a period of rapid growth to a period of modest growth. Maturity implies characteristics such as intensified competition for market share, and incremental innovations in product and production process (Porter 1980). The construction equipment industry comprises a broad range of equipment. Earthmoving equipment is a segment of the construction equipment industry that includes crawler loaders and dozers, wheel loaders and dozers, scrapers, graders, hydraulic excavators and backhoes, trenchers, pipe layers, and off-highway trucks. This could be a more exact term for these equipment, but the generic term "construction equipment" is used throughout this paper.

The construction equipment industry is dominated by North American firms, six of which hold more than 70% of the value of sales in the world (Standard and Poor's 1995). Caterpillar is by far the leading producer of construction equipment and is believed to control more than 45% of the U.S. market and 35% of the world market (Standard and Poor's 1995). Komatsu is the world's second-largest producer of construction equipment. The other important manufacturers are Case, Clark, Deere & Co., and Hitachi.

The construction industry is the key user of earthmoving equipment; other users are in the mining and forestry sectors. A review of *Standard and Poor's Industry Surveys* on steel and machinery over the 1976–95 period indicates that the demand for this equipment is highly correlated to the level and type of activity in the construction market. The end of World War II witnessed a boom period for megaprojects such as highways, housing, water management programs, and other big-scale projects that, in turn, boosted demand for construction equipment. In the 1970s, most of the developed countries completed their megaproject programs. During the same period, oil-rich Middle Eastern countries benefited from higher oil prices and initiated megaprojects for their infrastructure development. The impact of declining oil prices in 1982 was not only confined to those countries, but also caused a decline in the global construction market with a proportional decline in the demand for construction equipment. The recovery in the U.S. construction markets in 1983, which was fueled by relatively lower interest rates, increased demand for construction equipment and stiff competition continued (Standard and Poor's 1984). But, the end of the megaprojects era in the second half of the 1980s caused the demand to shift to versatile and small equipment. Weaker construction markets coupled with worldwide recessionary conditions in the period between 1987 and 1991 resulted in losses for many construction equipment manufacturers. The modest improvements in the U.S. construction market and the strengthening of the foreign market in 1992–93 stimulated increases in the sales of construction equipment (Standard and Poor's 1995).

The construction equipment industry is clearly affected by market conditions, i.e., by ups and downs in construction ac-

[1]Prof., Dept. of Civ. and Arch. Engrg., Illinois Inst. of Technol., Chicago, IL 60616.

[2]Grad. Student, Dept. of Civ. and Arch. Engrg., Illinois Inst. of Technol., Chicago, IL.

[3]Grad. Student, Dept. of Civ. and Arch. Engrg., Illinois Inst. of Technol., Chicago, IL.

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tivity and by the size and type of construction projects undertaken. But it is also affected by technological innovations in fields such as materials, metallurgy, mechanical systems, electronic sensing, and hydraulic controls. The construction equipment industry focuses on the continuous improvement of its products by introducing advanced technology, which includes incorporating electronics and advanced fluid and mechanical power actuation for quick response, higher operation efficiency, and diagnostic capabilities.

OVERVIEW OF INNOVATION

Derived from the Latin word *novus*, or new, the term "innovation" has a number of related meanings. It is alternatively defined as "the introduction of something new" or "a new idea or device" (Tornatzky and Fleischer 1990). Innovation is analyzed in the following sections under three headings: impact of innovations on bringing changes, intersectoral patterns of innovation, and the driving forces in the innovation process.

Impact of Innovations on Bringing Change

In terms of their impact on bringing about change, innovations can be classified into three groups (Freeman 1974): incremental innovations, radical innovations, and revolutionary innovations. Incremental innovations involve a smooth continuous process leading to steady improvements in the product or process. Radical innovations involve the establishment of totally new products of processes. Revolutionary innovations cause significant economic changes. Pavitt (1971) emphasizes that revolutionary innovations do not happen at regular time intervals, and that incremental innovations are much more common. Abernathy and Utterback (1978) further state the cumulative and gradual importance of incremental innovations, asserting that half of an innovation's advantage over predecessor technology is obtained through many minor modifications, since innovations do not emerge in their final form but continue to develop and improve. Rosenberg (1982) argues that the importance of incremental innovations is underestimated. Kline and Rosenberg (1986) also suggest that while some technological changes are in the form of highly visible major innovations, such technological change is less visible and even invisible in many cases. These invisible innovations can take the form of very small changes, such as instituting minor modifications in the design of a machine to provide better service to the end users, improving performance characteristics, changing production methods to shorten production time, substituting a cheaper material to lower the manufacturing cost, rearranging the sequence of operations, reducing friction and vibration for a higher cost efficiency and longer useful life (Kline and Rosenberg 1986).

Even though capital intensiveness, complex legal responsibilities, resistance to change, the fragmented nature of the industry (Rosenfeld 1994; Tatum 1986), labor-relations issues, safety considerations imposed by the Occupational Safety and Health Administration (OSHA), EPA regulations, and standard building codes (Laborde and Sanvido 1994) are commonly cited as major barriers against innovation in construction, innovations occur to a greater extent in construction than are usually recognized (Slaughter 1993). But the construction industry has traditionally been characterized as very conservative (Pries and Janzen 1995), probably because they occur incrementally over periods of many years and in many cases they are invisible. Male and Stocks (1991) argue that incremental innovations are much more common in construction, and that radical and revolutionary innovations are rare. This can be partly linked to the incremental nature of the innovations that take place in feeder industries, such as the construction equipment industry, since innovations in construction equipment have a direct impact on the state of technological advances in construction.

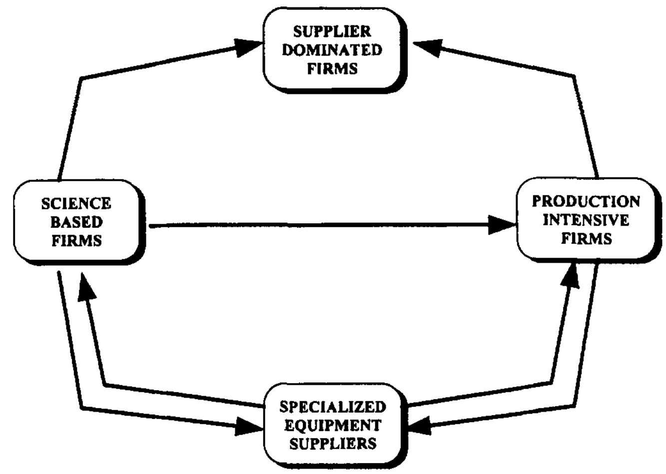

FIG. 1. Intersectoral Patterns of Innovations [Source: Pavitt (1984)]

Intersectoral Patterns of Innovation

The complex interdependence of technological exchange among sectors was first addressed by Schmookler (1966) who proposed a hypothetical two-way invention matrix, with sectors making inventions placed in columns and using these in rows. Schmookler's invention matrix promoted several studies on intersectoral patterns of innovation in the context of different countries [Scherer (1984) in the United States, Pavitt (1984) and Robson et al. (1988) in the United Kingdom, and Archibugi et al. (1991) in Italy]. The pattern of the flow of innovations among sectors is identified by distinguishing innovations that are directed toward improving the mode of production in a sector as "process innovations," and innovations that are produced in one sector and used in another as "product innovations." A review of these studies reveals that the intersectoral flow of innovations follows a pattern whereby the core sectors—such as the chemical, electrical/electronics, and machinery and instrument sectors (including the construction equipment industry)—appear to play an important role in generating most innovations. Pavitt's (1984) taxonomy of sectoral patterns of technological change explains the general characteristics of a pattern of flow common to many industrialized countries (Archibugi et al. 1991). It examines organizations in four groups: supplier-dominated firms, science-based firms, production-intensive firms, and specialized equipment suppliers (Fig. 1).

Supplier-Dominated Firms

These make use of technologies developed by feeder industries and are heavily dependent on the innovations of science-based firms, such as those that manufacture chemical and electrical/electronic products, and production-intensive firms, such as those that manufacture machinery and instruments. In some cases, some of the innovations originate from large customers and government-financed projects. A relatively high proportion of the innovations in supplier-dominated firms are directed toward process innovations such as development of cost-cutting methods. Construction companies show the characteristics of supplier-dominated firms.

Production-Intensive Firms

These can be categorized into two groups, namely, scale-intensive firms and mechanical and instrument engineering

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firms. Scale-intensive firms, such as those that manufacture metal, synthetics, glass, and cement products, produce a high proportion of their own process technology. The price is important to users once certain performance requirements are met; therefore, the primary focus is "process innovation" rather than "product innovation." Mechanical and instrument engineering firms produce a high proportion of their own process technology, but their main focus is product innovation for the use of other sectors. Performance and reliability are assigned a higher priority relative to purchase price. Construction equipment manufacturers fall into this group.

Science-Based Firms

These manufacture products such as chemical and electrical/electronic components. They focus on R&D for technological change and play a dominant role in producing innovations for use in their own sector as well as in other sectors. Universities and research institutes are the main driving force in this process. Production-intensive firms get innovation from science-based firms.

Specialized Equipment Suppliers

These provide equipment and instruments for production-intensive and science-based firms and have complementary relationships with them. These firms have reciprocal interdependence for innovation with specialized equipment suppliers.

Construction companies, as supplier-dominated firms, are heavily dependent on science-based firms for innovations in electronic goods and plastics and on production-intensive firms for construction materials and equipment. Construction equipment manufacturers, which can be classified as production-intensive firms, provide technical system innovations to the construction sector. They also receive innovations from specialized equipment suppliers and from science-based firms, particularly in electronic controls.

Driving Forces in Innovation Process

The rate and type of technological change in an industry are the result of environmental dynamics acting on that industry (Fig. 2). A host of environmental factors put pressure on firms to generate and implement innovations. The strategic decisions, production practices, marketing policies employed by firms, and government regulations represent the market-pull side of the argument, and R&D represents the technology-push side. The cause-effect relationships in this dynamic process are complex in nature.

Technology push and demand pull constitute the continuing debate underlying motivation and driving forces behind innovation. The technology-push school of thought is based on Schumpeter's ideas and places the major role of creating innovations, on technology. On the other hand, the demand-pull school of thought is based on Schmookler's (1966) study and suggests that firms perceive profit opportunities on the market and innovate in order to maximize profit; thus the market (not the scientific base) is the prime driver of innovation. The empirical research studies on innovation are inconclusive regarding the technology-push and demand-pull debate. Chidamber and Kon (1994) argue that the major studies on the technology-push and market-pull theories were carried out in the 1970s and that today's environmental dynamics are different from those of the 1970s.

They also point out that the 1950s and 1960s were periods of heavy investment in R&D, and that innovation activity in the 1970s may have been skewed toward market-oriented incremental innovations built on the foundations created by previous scientific research. Pavitt (1984) emphasizes that the technology-push and market-pull debate can be better reconciled by analyzing these driving forces in the context of characteristics of the sectors as depicted in Fig. 2. Pavitt (1984) emphasizes that innovations in production-intensive firms such as construction equipment manufacturers are driven by demand-pull factors.

Government regulations have strategic implications for any

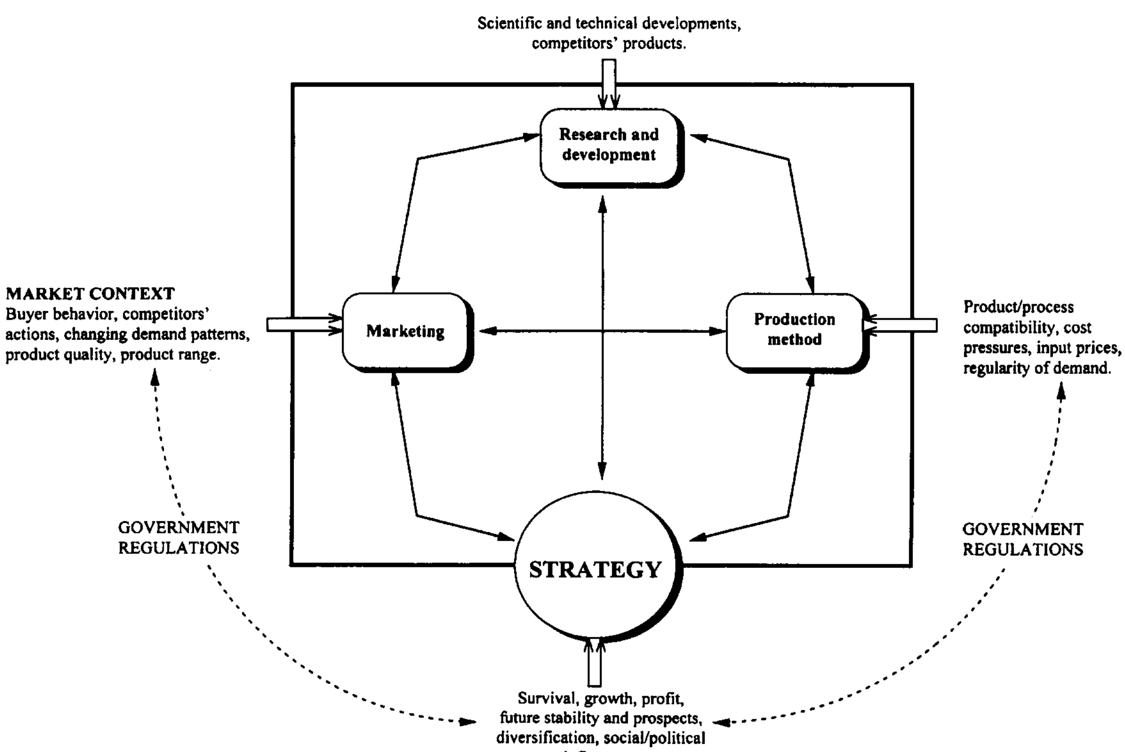

FIG. 2. Effects of Environmental Dynamics on Innovation [adapted from Coombs et al. (1989)]

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firm. While a vast array of regulations exists in the United States, environmental and health and safety regulations have an overarching influence on the products and production processes of the construction equipment industry. The common view that considers government regulations as an important barrier against innovations has been recently challenged by Porter and van de Linde (1995). The theoretical base of their argument is that properly designed regulations will act as a catalyst for innovations, improve products and processes, and lead to cost reductions. For example, environmental regulations impose emission standards and noise reductions; OSHA regulations that have to be met when operating construction equipment constitute an important input in designing these equipment. Innovating to meet these imposed performance criteria represents a demand-pull force acting on the construction equipment industry.

A firm's response to environmental dynamics is formulated through its strategy, since the essence of strategy is to relate a firm to its environment. Porter (1980) suggests that in an industry, firms can adapt any three generic strategies that might lead to success of business—cost leadership, focus, and differentiation. According to Hambrick's (1983) empirical study, the cost leadership strategy that places emphasis on process innovations is not viable in the construction equipment industry, and product differentiation is its primary means of survival and success. The underlying reasons behind this argument can be explained by using Sousa and Hambrick's (1988) taxonomy, which operationalizes the mature industrial-product sectors (including the construction equipment industry) along two dimensions: production method employed and market context.

The dynamic interaction between strategy and production method is well recognized in the literature (Skinner 1979; Kantrow 1980; Abernathy and Utterback 1978; Utterback and Abernathy 1975). Hayes and Wheelwright (1979) explain how technology frames strategy, or strategy demands certain technological developments. Production methods are classified by Woodward (1965) as small-batch, assembly-line, and process methods. The production method used in the construction equipment industry has the features of an assembly-line operation—most of the operations required in the production process are performed in a line. The flexibility of the assembly-line production method creates opportunities for construction equipment manufacturers to maximize product quality through continuous improvement.

The market context dimension is represented by three highly correlated variables: frequency of purchase, buyer-seller interaction (time and number of people involved in a purchase), and risk of product malfunctioning. The industrial marketing literature suggests that the first two variables are closely linked to each other: the more frequent the purchase, the less time and number of people will be involved in purchasing. In the construction industry, equipment decisions are commonly made by committees that are composed of high-level management and technical personnel. A recent survey by Romanek and Enabbit (1993) reveals that two to ten or more people are involved in making equipment purchase decisions. The survey also highlights that the most important criterion in the purchase decision is product quality and the least important is price. The long-term life-cycle cost of the products also forces the user to demand more efficient products. The risk of product malfunctioning is related to complexity (skills required in operation and number of moving parts) and uncertainty (operating in different environmental conditions, with different operating styles). The higher the complexity and the uncertainty, the greater the risk of product malfunctioning. The service, reliability, and durability of the equipment are important for contractors since breakdowns can cause significant project delays, can increase the frequency and severity of claims considerably, and can be conducive to escalating costs.

Therefore, it appears that in the construction equipment context, the frequency of purchase is low, the number of people involved in the purchase decision is high, the risk of equipment breakdown is high, and the assembly-line method of production is prevalent. As a direct result of these characteristics, the construction equipment industry is expected to concentrate its efforts primarily on product-oriented R&D aiming at continuous improvement of products and thus leading to incremental innovations.

Government regulations, the market context, and the production methods used are not the only stimuli for continuous product innovation in the construction equipment industry. Technological advances produced by other industries—more specifically, by science-based firms and specialized equipment suppliers—provide opportunities for innovations in earthmoving equipment that manufacturers have to respond to in order to survive and prosper.

RESEARCH METHODOLOGY

In previous studies of innovation, different research methodologies were used, such as reviewing professional journals (Nam and Tatum, 1992; Von Hippel 1988), conducting surveys through questionnaires (Archibugi et al. 1991), and interpreting the number of registered patents and R&D expenditures (Scherer 1984). The possibility of introducing bias into studies of innovation that make use of subjective criteria is emphasized by Nam and Tatum, since what is considered an "innovation" by one may not be interpreted as such by another. To overcome bias in this study, objective measures were used. The rate of innovation in construction equipment is measured by using two variables over a 30-year study period: the number of new models introduced every year and the technological life of particular equipment. In a study by Miller (1988), the rate of innovation was measured by the number of new products introduced in a given year. However, it alone cannot be a true measure of the rate of innovation, since neither imitation of newly introduced products nor cosmetic product innovations by competitors should be considered product innovation. That is why the second factor of technological life has been introduced in this study. Here, "technological life" is defined "the length of time that an equipment's technology is state of the art." In other words, the technology of an existing model is more efficient than the technology of the preceding model, but will be superseded by the technology of the succeeding model.

The equipment investigated in this study include eight earthmoving equipment, namely, hydraulic excavators (backhoes), wheel-mounted backhoes/loaders, four-wheel drive loaders, two-wheel front or rear drive loaders, four-wheel heavy-duty dozers, crawler loaders (with loader front), and crawler dozers (with angle dozer or bulldozer). The data regarding the selected equipment were extracted from several editions of the AED Association of Equipment Distributors (AED) *Green Book* (1986–92). Data were available for the years 1963–92 for hydraulic excavators; 1970–92 for wheel-mounted backhoes/loaders; 1961–92 for four-wheel drive loaders; 1962–92 for two-wheel front or rear drive loaders; 1965–92 for four-wheel heavy-duty dozers; 1965–92 for crawler loaders; and 1958–92 for crawler dozers. More than 60 manufacturers were involved in producing these equipment over the respective years.

Linear regression was performed to observe the trends of the two variables: "new models launched every year" and "technological life" over the 30-year study period for all eight types of earthmoving equipment considered here. MS Excel for Windows 95, version 7.0 was used for this purpose. The results are presented in Figs. 3 and 4. Different scales are used on the y-axes in Fig. 3(a–g) because of the significant differ-

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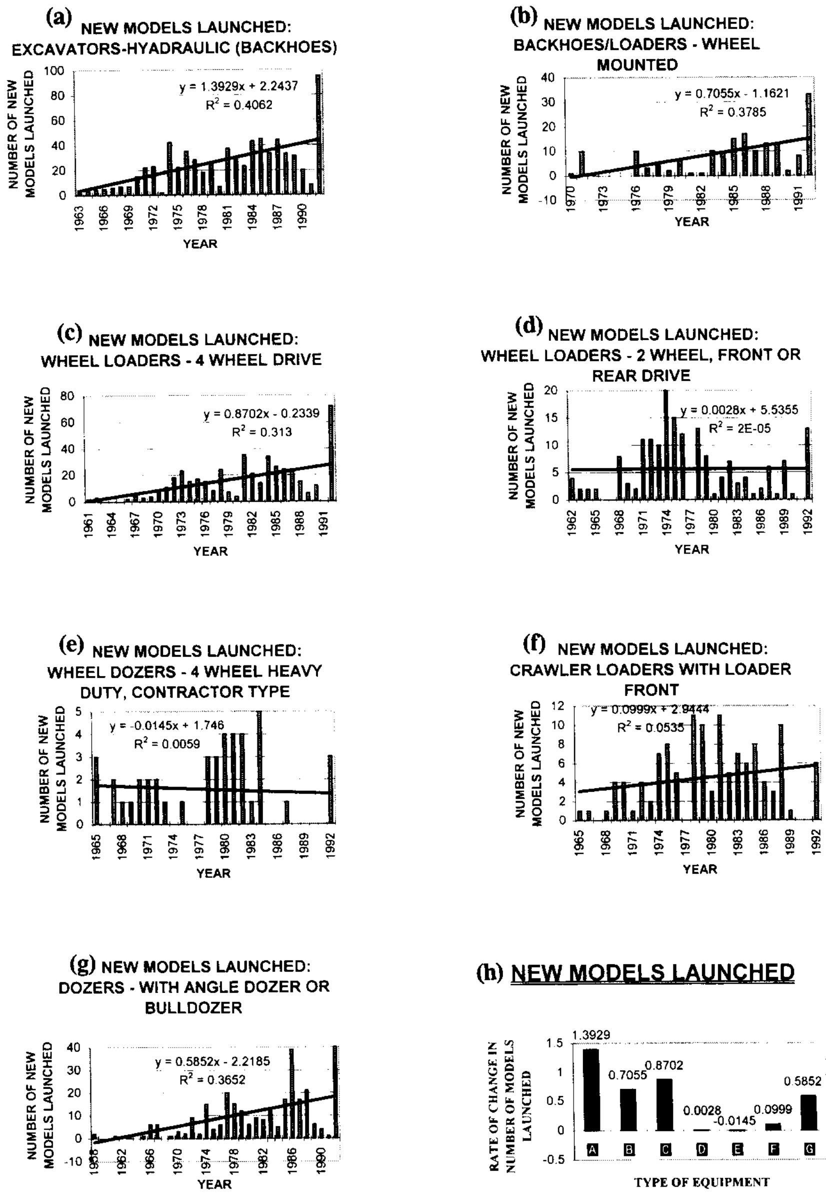

FIG. 3. Regression Analysis of New Construction Equipment Models Launched

ences in the annual data associated with each type of equipment considered in the study.

RESULTS AND COMMENT

The hypothesis tested is whether the rate of innovation in the construction equipment industry is increased over the 30-year study period. The linear regression analysis performed on the number of new construction equipment introduced over the 30-year analysis period [Fig. 3(a–g)] does not provide a statistically significant fit at 1% for any equipment considered, but it is observed that the number of new pieces of earthmoving equipment introduced every year increased substantially over the last 30 years [Fig. 3(h)]. The regression analysis performed on the technological life of the construction equipment considered here provides a statistically significant fit at 1% for all equipment (Fig. 4).

The findings presented in Figs. 3 and 4 indicate that the rate of innovation in construction equipment has increased over the last 30-year period. In the last 30 years, the continuous and moderate decrease in the technological life of all construction equipment studied in the research (regression lines with negative slopes, statistically significant at 1%) suggests the occurrence of innovations that are incremental in nature. Since these innovations are incremental, it can be argued that they are primarily driven by market forces, not technology.

The basis of competition in construction equipment appears to be continuous improvement in the quality of the product. The manufacturer offering new construction equipment with improved technology can create a competitive advantage and generate profits from its quasi-monopoly position. The competitive advantage created on the basis of a new product is not sustainable for long periods of time since the equipment operates on site and can therefore be easily imitated by competitors. The imitation period during which a firm can sustain its competitive advantage is of the order of one year (Von Hippel 1988). A firm losing its competitive edge immediately focuses on introducing improved products to regain its competitive advantage. This cycle that fuels incremental innovations is termed "acceleration trap" by Von Braun (1990), who also states that the acceleration trap may have negative economic implications for innovative firms.

Although the technological lives of the construction equipment presented here have significantly declined over the 30-year study period, it is unlikely that this rate of decline will continue, since the lower limit of the technological life of an

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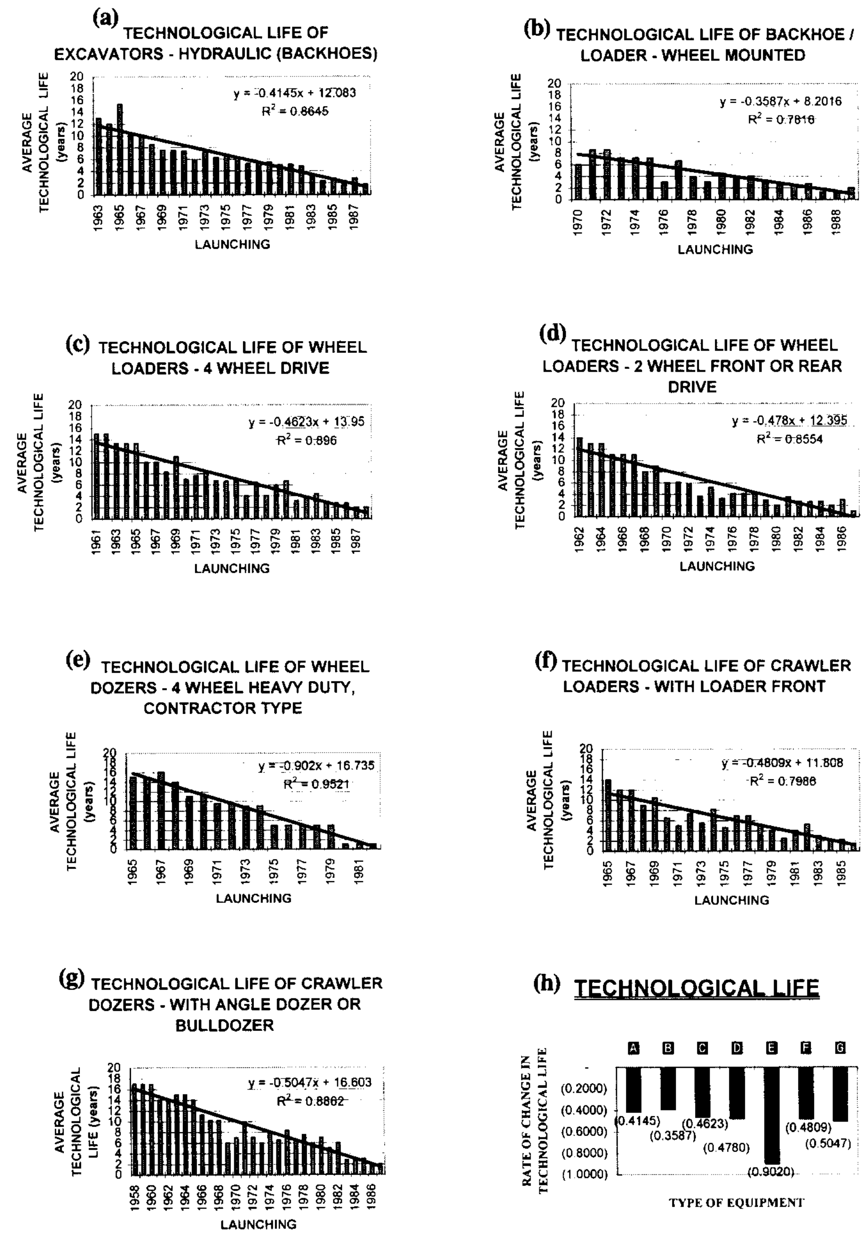

FIG. 4. Regression Analysis of Technological Life of Construction Equipment.

equipment cannot be smaller than zero. As the technological life approaches zero, limitations in a firm's resources and in the market's absorption capacity are expected to slow down this decline (Von Braun 1990).

As new technologies are developed, new construction equipment become possible. To the extent that these equipment provide better value to the customer, they will replace older equipment. The period between introducing new construction equipment models in the market and discontinuing them is getting shorter because of more rapid technological obsolescence and increased pressures from competitors.

The increased rate of innovation in construction equipment is partly stimulated by contractors' needs, partly by advances in technologies developed in the construction equipment industry, and partly by the transfer of technologies from other industries—particularly the electronics industry, which creates impetus not only for new product design but also for flexible and rapid production methods. In today's competitive arena, factors including engineering excellence, production efficiency, and product quality are key to sustainable success; indeed, the executive leaders of some construction manufacturers acknowledge that focusing on contractors' needs is the key to success in the 1990s (Green 1990) and will continue to be important in the future (Fites 1996). Innovations in construction equipment include advances in hydraulic systems, incorporation of microprocessors in drive and attachment functions, user-friendly control systems, load-sensing hydraulic systems, improved engine performance through turbo and other supercharging systems, modular construction in mainframes, components and subassemblies, improvements in visibility, comfort, safety, and greater versatility. New electronics based technologies—such as computer-aided design (CAD), computer-aided engineering (CAE), computer-aided design for manufacturing (CADFM), and computer-integrated manufacturing (CIM)—have provided for the introduction of new products on accelerated schedules. Simulations (virtual reality) let equipment manufacturers test new designs before building physical prototypes and before performing extensive tests early in the design process. The flexibility and rapid applicability of design and production methods also fuel the incremental innovations observed in the construction equipment industry. Advances in instrumentation technologies, such as refractometrics, vertical presetters, and probes, increase the lead time in the production process and also provide greater

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accuracy of production along with methods of data gathering and presentation.

The paramount importance of innovations in construction is well recognized, improving quality of life, competitiveness, productivity, and safety (Laborde and Sanvido 1994). The studies on innovation (Pries and Janzen 1995; Pavitt 1984) reveal that the construction sector is dependent on other sectors for innovations. However the nature of this dependency needs clarification. Following Hunt (1972), Male and Stocks (1991) distinguish between "technology" and "technical system" when analyzing innovations in construction. According to Kast and Rosenzweig (1985), "Technology is the organization and application of knowledge for the achievement of practical purposes and includes physical manifestation such as tools and machines but also intellectual techniques and processes used in problem solving and obtaining desired outcomes." On the other hand, Hunt (1972) states, "The technical system is the collective instruments introduced into the action system, including all physical influences which operate in conjunction with members but which are themselves systems independent of members." In the context of this terminology, construction companies are principally technological innovators and are dependent on feeder industries for technical system innovations (Male and Stocks 1991). As a technological innovator, the construction sector plays a dominant role in initiating innovations for new construction methods and processes (Nam and Tatum 1992); finding alternative corporate structures (Lansley 1991); financing methods such as countertrade, confinancing with the World Bank, swap financing, and project financing (Munisteri 1987; Yates 1990); and seeking ways to deal with interorganizational disputes, such as alternative dispute resolution methods (Readey 1991) and alternative project delivery systems (design-build, construction management, and build-operate-transfer). A research study on innovation in construction (Pries and Janzen 1995) reveals that most of the innovations in construction are process oriented, and therefore support the assertion that construction companies are technological innovators.

Technical system innovations, on the other hand, are beyond the control of the construction industry (Laborde and Sanvido 1994). Construction companies are dependent on the electronics, machinery, and chemical sectors for technical system innovations. Understanding the nature of innovative activity in these sectors is important because technical system innovations present new opportunities for the construction sector. The finding in this study that the rate of innovation has been increasing over the last 30 years in the construction equipment industry is of particular interest when its impact on technological advances in the construction industry is analyzed.

CONCLUSION

There is enough historical evidence to state that innovation in the construction equipment industry is partly a demand-pull phenomenon fueled by market conditions. The competitive strategy of construction equipment manufacturers, which is framed by the production methods they use (assembly line) and the buyers' behavior (low purchase frequency, large number of people involved in the purchase decision, and high risk of breakdown), appears to be the driving force for fueling incremental innovations. On the other hand, it is also a case of technology push since it is clear that the construction equipment industry depends on other industries for technological advances.

Technological advances are not confined to the industry that produces the innovation. Construction companies that are categorized according to Pavitt's (1984) taxonomy as supplier-dominated companies depend heavily on innovations produced in other industries—namely, production-intensive and science-based firms—for technical system innovation. The mapping of this dependency particularly highlights the flow of innovations from the construction equipment industry that is actually composed of production-intensive manufacturers. Since improving construction processes and methods necessitates more advanced equipment, the rate of innovation in the construction equipment industry has a direct impact on the state of technological change in the construction industry.

The findings of the study presented here suggest that the rate of innovation in the construction equipment industry increased during the last 30 years. This increased rate of innovation can be linked to pressures generated by buyers' behavior and to technological developments in the equipment industry as well as in other industries. The findings also indicate that the rate of innovation has been uniform and incremental over these 30 years. Even though innovations in the construction equipment industry are incremental in nature, their cumulative benefits can be enormous because incremental innovations result in continuous improvements in product features. These incremental innovations are primarily driven by market forces.

Innovations in construction equipment are bound to generate significant benefits for construction companies that purchase and use advanced models. Improvements in site productivity and safety, in the quality of working conditions, and in the company's cost-efficiency and competitiveness can be partly explained by these incremental innovations.

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