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Major characteristics of constructed products and resulting limitations of construction technology

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The products of construction differ in many important ways from those of manufacturing. This paper describes five major characteristics of constructed products: immobility, complexity, durability, costliness, and high degree of social responsibility. These characteristics result in many limitations for construction technology; this paper analyses two of these limitations: the consequences of site operations and specialization. These characteristics suggest both insights regarding directions in developing construction technology and practical applications.

Keywords: Construction technology, constructed product, innovation, mass production, integration

Introduction

Many researchers have identified unique aspects of the construction industry in comparison with other industries. For example, 'field oriented' (Paulson, 1985), 'extremely conservative' (Rosenberg, 1982), 'too many small firms' (Cassimatis, 1969), 'fragmented' (Barrie and Poulson, 1978), 'technologically stagnant' (Business Roundtable, 1982b), 'negligible R & D' (National Research Council, 1986). However, further examination of construction technology suggests that these are merely partial descriptions of the *results* of the differences in the characteristics of constructed products and the resulting limitations of construction technology. Increased understanding of the significant characteristics of constructed products and how these characteristics influence both construction technology and the potential for its advancement is an important element of increased technological competitiveness of the industry.

The purpose of this paper is to examine the fundamental *causes* of the technological phenomena of construction. We describe the major characteristics of constructed products and examine their consequences for construction technology. Also, the paper reviews some efforts to overcome the technological restrictions inherent in constructed products.

The background research for this paper is part of an ongoing investigation of mechanisms and strategies for technological advancement and increased competitiveness in construction (Tatum, 1986). This research project includes three major elements: developing a classification system for construction technology (Nam, 1987; Tatum, 1988); constructing models of processes for innovation in construction, and testing these models using examples of both process and product innovation (Tatum, 1987b, 1987c; Tatum and Funke, 1987);

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and formulating strategies for the use of technology to gain competitive advantage in changing construction markets (Tatum, 1987a).

The paper begins by describing key characteristics of constructed products: immobility, complexity, durability, costliness, and social responsibility. We then examine consequences of these characteristics: limitations on mass production, regionalism, seasonalness, the 'locked system', and separation of design from production. The paper concludes by highlighting implications of these characteristics and their consequences for researchers and industry professionals.

Characteristics of constructed products

Colean and Newcomb (1952) found that the products of construction, despite the wide diversity of the sectors within the industry and the heterogeneity of each product, share certain common characteristics: they are immobile, complex, durable and costly. Lange and Mills indicate the following product characteristics in construction: 'assembly at a particular site', 'high diversity of technological requirements of varying degrees of complexity' (1979, p. 4). Also, the construction literature suggests that constructed products are highly related to the public safety and health, compose a major part of the human environment, and carry an immense social responsibility (Knowles and Pitt, 1972; Garnham, 1983; Harper, 1985).

Therefore, understanding construction technology requires us to probe the following major characteristics of constructed products: (1) immobility, (2) complexity, (3) durability, (4) costliness, and (5) high level of social responsibility. These characteristics differ for the various kinds of constructed products, but in some degree they are present in most. The following sections will discuss each of the characteristics and identify their sources and the immediate results.

Immobility

Historically, construction refers to all types of activities associated with the erection and repair of *immobile* structures and facilities. The US Department of Commerce employs this characteristic of immobility as a criterion in defining construction. For example, *1982 Census of the Construction Industry* (US DOC Bureau of the Census, 1984) claims that even though ships are heavy, durable, complex and costly goods, shipbuilding is not classified as construction since ships are movable. For the same reason, data regarding mobile homes and travel-trailers are included in the manufacturing census rather than that of construction.

In the manufacturing industry the finished products are transported to the market place. In contrast, the production process of construction usually takes place at the point of consumption, and the finished product of construction is generally immobile. Thus, construction is mainly a site operation. Modularization, one exception, has focused primarily on industrial construction (Williams, 1987) and parts of buildings (Tatum *et al.*, 1986).

Complexity

One way to measure the level of complexity of a product is to count the number of different materials required for the product. Colean and Newcomb (1952) recognized the extraordinary variety of materials required for the products of construction:

> Construction draws upon raw materials of nearly every type. These include farm products, like cotton, tung oil, . . . the full range of metals; forest products; numerous chemical compounds; and such common natural materials as sand, stone, and gravel. . . . For most of these, successive stages of refinement, combination, and fabrication are required before they appear in the . . . finished construction materials and equipment. Of these articles, the varieties are myriad. For instance, [there are] . . . [standard] 668 [varieties of] lavatory and sink traps, 1,225 of pipes, ducts, and fittings for warm-air heating and air conditioning, and 2,969 of pipe fittings (p. 26).

These authors presented several reasons for this complexity of constructed products. The tremendous variety of site conditions and finished structures dictates variations in composition. Further variety and specialty are created by the individual tastes of owners and designers. Thus, diverse kinds and types of materials, equipment, and their combinations are used. Also, suppliers must make diverse products available because of the slow change in tastes and the continued demand for repair parts for the durable products of construction. Therefore, in spite of efforts toward standardization and simplification, constructed products move toward increasing complexity and this necessitates more specialized knowledge.

As a consequence of this complexity of constructed products, a wide variety of specialization is necessary to handle these various materials. However, this professional specialization (especially vertical disintegration) in construction is a recent occurrence. According to Port (1967), designers, contractors, and materials producers were integrated around 1800. For instance, in the eighteenth century, bricklayers often made their own bricks. The vertical disintegration in construction began during the Industrial Revolution, which inspired some technological changes in construction, and was itself a product of the new methods and materials and the greatly increased scale of building.

As more complexity is added to the constructed product, more specialization results. In the US, for example, there are over 500 trade associations and professional societies in the construction and building materials industries ranging from large and well-known associations like the American Society of Civil Engineers to the small ones like the Steel Kitchen Cabinet Manufacturers Association (counted from *Construction Review* (US DOC, 1985)).

Durability

One of the distinguishing requirements for constructed products, in comparison with the products of the manufacturing industry, is that they must resist the forces of nature over an extended period of time. Thus, durability is not only a characteristic of constructed products but also a requirement. With adequate maintenance and repair, most constructed products are renewable and their physical life can be almost indefinite.

The economic consequences of durability are an inconsistent value partly due to immobility (Cassimatis, 1969) and a variable demand for constructed products since it is possible to defer replacement of a durable structure in times of doubtful economic outlook (Colean and Newcomb, 1952). Besides these economic consequences of durability, a technological concern is the fact that, to be durable, construction materials are usually bulky and heavy. These requirements for the materials of construction restrict the development of construction technology in many important ways.

Costliness

Complexity and durability lead to another characteristic of constructed products – costliness. This characteristic called for centralized authorities to control construction in ancient times. Nowadays, a house, for example, is still the largest single expenditure of an urban family.

The arguments regarding the reasons for the costliness of constructed products are diverse: the slow advancement of construction technology (Business Roundtable, 1982b); the increasing complexity; improvements in quality (Ventre, 1979); and peculiar behaviour of the construction industry (Rosefielde and Mills, 1979).

Will this costliness diminish as a characteristic of constructed products in the future? The current trend of increasing construction costs says not. However, it is fair to say that the possibility of decreasing costliness or immobility depends on changes in construction technology, given the seemingly natural tendency of increasing complexity and quality of constructed products.

The costliness and the durability of constructed products are responsible for another interesting phenomenon in construction. The construction market is less sensitive to novelties of constructed products as compared with manufacturing. That is, construction itself cannot induce the demand for its products. However, much of the technology literature indicates that either existing or anticipated market demand (Myers and Marquis, 1969) as well as supply-side mechanisms (Rosenberg, 1982) are a prerequisite for technological innovations. Thus, the inability of construction to create demand may be a barrier to the rapid advancement of construction technology.

Technological conservatism of designers and builders also results in part from the costliness of the constructed product. Considering the cost involved, it is not possible to destroy a skyscraper to test its seismic design. Even a reasonably testable model of a constructed product is very costly. The result is less trial and error in construction and more conservative design. Trying new methods and materials, without sufficient tests, on costly goods like constructed products results in high risk. Thus, the general tendency in construction is to use well-proven construction methods and materials.

High degree of social responsibility

The products of construction carry a high degree of responsibility to the public. This social responsibility stems from many sources and increases both conservatism in design and specialization among contractors.

Source of social responsibility. The history of construction-related regulations (Knowles and Pitt, 1972; Garnham, 1983; Harper, 1985) suggests that heavy social responsibility for constructed products results from both the concern for public safety and health and the growing awareness of environmentalism.

When cities began to form, constructed products became the target of government regulations since designers and builders were thought to lack concern for public safety. Fires (due to flammable materials and crowded configurations of buildings) and diseases (especially cholera due to contaminated water supply and inadequate drainage systems) provided additional incentives for regulation (Harper, 1985). Thus, most of the construction-related regulations were concerned with controlling the spread of fire (e.g. restrictions on the use of external wooden ornamentation), controlling dangerous structures (e.g. restrictions of encroachments into the streets), and protecting the public health (e.g. enforcement of sanitation, controls on space around buildings, room heights, and window sizes) (Knowles and Pitt, 1972).

Recently, the disastrous collapse of structures, automobile accidents due to the design of highways, and serious accidents at nuclear power plants are causing increased emphasis on social responsibility in producing constructed products. The growing attention to environmental protection also increases the social responsibility of constructed products. This concern focuses on constructed products because of their durability and costliness. Mistakes in constructed products fester 'in the form of ugliness, pollution, disease' (Strassmann, 1978, p. 264). The remedies for these construction blunders are so costly that they often remain as a form of environment. Churchill had an insight on this: 'We shape our buildings; thereafter they shape us.'

Ultra-conservatism. The consequences of social responsibility for constructed products are ultra-conservatism, proliferation of government regulations, and the need for checks and balances (or for distribution of responsibility) among various team members. The traditional attitude of ultra-conservatism that stems both from the costliness and the high level of social responsibility of constructed products is not only shown by the producers; it has also been the attitude of consumers. For example, 'so traditional are consumers' preferences when it comes to their own housing, [thus,] the threat of adverse consumer reaction is the primary inhibiter to innovation by builders; many housing producers do their best to shield from view changes in technology that have already been absorbed into their production methods' (Ventre, 1979, p. 51).

Specialization. Another result of the increasing social responsibility of constructed products is that one specialty is often barred from doing another specialty's work by a licence system. It is a legal system designed to guarantee the necessary competence of each specialty to provide a safe and healthy environment to the general public. This concern for public safety, health, and welfare is another historical reason that has spurred the specialization in construction. Bowley (1966) explains that during the period of the Industrial Revolution construction too often caused fraud and catastrophe. Thus, the specialization was needed in order to separate the powers with legal checks and balances and to increase safety.

Up to this point our discussion has focused on the characteristics of constructed products, their sources, and the immediate results. These results are summarized as the requirement for site operations, the need for specialization, the necessity to use bulky and heavy materials, and the resulting conservatism in the construction industry. The next sections of the paper will describe the consequences of these constraining factors for construction technology. This description focuses on the requirement for site operation and the need for specialization because these two factors significantly impact technological development in construction.

Technological consequences of site operations

The immobility of constructed products prevents their production in the factory environment. This leads to many unique features of construction technology. We will discuss three: limitations on mass production, regionalism, and seasonalness.

Limitations on mass production

Variations in site conditions and owners' needs make most buildings unique. Each facility has to be designed and produced to meet the requirements of a particular site. Immobility thus contributes to the non-uniformity of products and, coupled with the increasing complexity of construction materials, increases the difficulty of standardizing constructed products.

Without standardization it is not possible for construction to use a mass production system, which has long been one of the key means to increase productivity and product quality in the manufacturing industry. Nowadays, mechanization plays an essential role in many construction processes. Automation is being applied in limited areas of construction. However, construction has never enjoyed the use of mass production systems to fully automate its production process.

Efforts toward mass production

Standardizing components of constructed products, rather than the whole product, has brought some success. A wide variety of prefabricated and standardized concrete products are available: masonry blocks, paving stones, and pre-stressed concrete beams. Also standardized building components (doors, windows, building equipment, etc.) are commonly used. Recently, the development of panelized construction or modularization, used with heavy lifting equipment, has modified one of the unique characteristics of construction – immobility. The trend in construction production is clearly moving on-site processes to off-site factories. However, the characteristics of buyers and the use of bulky and heavy materials in constructed products block the use of mass production in a factory environment. A description of these barriers follows.

A barrier – individual taste. Constructed products are a major part of our physical environment. Even if they are not monuments, buildings can create strong emotional responses. Thus, it is natural for people to want to have their individual tastes reflected in the products before they are produced.

However, the term 'mass-produced' implies some consistency or conformity, which customers dislike, especially when the product is a durable and costly good. Strassmann warns of neglecting the importance of individual tastes: 'It is easier to crowd another mobile home in the slot between two others. In a decade or so, salvaging abandoned mobile homes may be a regular industry' (1978, p. 264). The wide variety of individual tastes, which is partly responsible for the complexity of construction products, is clearly one of the barriers to mass production.

A barrier – bulky and heavy materials. Mass production, which implies a transition from field production to factory production, necessitates the transportation of products or components of products from the factory to the site. However, in order to effectively withstand the forces of nature, most constructed products should be durable. Therefore they are mostly bulky and heavy. High transportation costs prevent moving such materials over great distances.

Possible solutions. There may be some solutions. The *Construction Review* (US DOC, 1985) reports that a design/construction firm produces metal buildings using standardized components and maintains acceptable appearance and function. Every building the firm produces is individually designed and manufactured based on engineering data covering cost and size specifications for all standardized materials and components stored in the company's computer system. The data processing technology therefore partially overcomes the increasing complexity of constructed products caused by the diversified tastes of customers.

The problem caused by durability is not yet unravelled. New advances in transport technology are needed to move the heavy and bulky building materials and components to the construction sites. The development of lighter-weight construction materials and components will partly alleviate the demands on the transport system.

Regionalism

Site operation subjects structures to local regulations (i.e. building codes) and requires contractors to be familiar with local subcontractors, local labour and locally available materials. The consequence is an incentive for construction firms to limit the geographical area over which they operate.

The regions with the most rapid growth in population and industrial output generally have the highest rates of increase in construction activity (Moody, 1982). Some construction companies, particularly those with special capabilities, may be able to shift their operations from one region to another in response to changing market conditions. However, most construction companies compete mainly in their local or regional markets. The *1982 Census of Construction* (US DOC, Bureau of the Census, 1984) reported that only 16% of construction receipts came from work outside home states.

Regionalism and easy entry to the construction industry contribute to the small size (in terms of value of work performed and employment) of most construction establishments. In 1982 firms with business receipts of more than $1 million numbered only 50,000, or 3.7% of the total construction establishments. Among 1.4 million construction establishments in the United States in 1982, 933,000 had no payroll (they are non-employers) (US DOC, Bureau of the Census, 1984).

Seasonalness

Much of the work of construction must be done in an open site because of the immobility of constructed products. This causes seasonalness in construction operations since construction processes are affected by temperature, wind velocity, precipitation, and ground water. It is obvious that the intermittent, seasonal nature of construction activity constitutes uneconomic underutilization of construction resources, and increases construction costs. This is also one of the reasons for low levels of capital investment by construction firms.

However, technological barriers are no longer the major obstacle to all-weather construction (one exception is the compacting of embankments and fills using soils with a high percentage of frozen material). The extra costs of the all-weather techniques vary greatly and may not be economical, but in many cases are not out of line with the benefits achieved (Martin, 1970).

The techniques most applicable for coping with weather problems include: (1) enclosure (by polyethylene, vinyl, etc.) and heating of construction sites; (2) insulation of structures, materials and workers; (3) heating of materials such as the components of concrete (US DOC, 1970, p. 5); and (4) development of new materials (e.g. air entraining agents to increase the durability of the concrete).

Technological consequences of specialization

Early in this paper, we identified the wide variety of occupational specialties required in construction as a consequence of the complexity of the constructed product and the concern for public safety. Bowley (1966) argues that this specialization, which she called the 'system' or a set of barriers among owners, designers, builders, materials producers, and others, was responsible for paralysing many types of technological innovation. Therefore, in order to understand construction technology, it is necessary to comprehend non-technological aspects as well – the dynamics and complexity of this 'system' (in a modern sense rather than that of Britain before the First World War as studied by Bowley).

This section will discuss the 'system' that is a hindrance to technological progress in construction, followed by a review of efforts to break down this 'system'. The last section will discuss another barrier caused by specialization in construction: separation of design from production.

The 'locked system'

The system is locked to any attempt to change the status quo. Innovation and diffusion are both a kind of change to the status quo. Many diffusion theories specify some favourable characteristics of an innovation that expedite diffusion and some conditions that determine the rate of diffusion for an innovation. For example, for rapid diffusion, an innovation should be compatible with potential adopters' values and beliefs, previously introduced ideas, and needs; not too complex to be understood; triable; and observable (Rogers, 1983). The conditions that determine the rate of diffusion are favourable communication channels so that potential adopters are fully informed about the innovation; potential adopters consider the innovation rationally optimal to use; and demands on potential adopters that create a situation too critical to ignore the innovation (David, 1969).

A major assumption of these diffusion theories is that a potential adopter is an individual or a group that lines up to make an S-shaped diffusion curve. However, if the adopter is not an individual or a group, but rather a *system* in which every actor acknowledges that others have heterogeneous goals, this system may regard an innovation as a force that upsets the equilibrium state. Changes in this system through the rapid diffusion of innovations are difficult. The system is locked.

This helps explain why a construction innovation that is technologically superior is not always adopted as rapidly as diffusion theorists, economists, or engineers may anticipate. Adoption also depends on economic and social institutions, on who has more control of the 'system' under what kind of endogenous factors (e.g. degree of unionization, cohesiveness, or strength of specialty contractors' association, etc.), and on exogenous factors (e.g. collapse of a building, a slow-down in the economy, construction cost increases, the invasion of foreign construction firms, etc.) that determine each actor's level of power.

The actors in the system include various owners; the government as the largest buyer of construction and a conservative representative of the public to protect its safety and health; numerous specialized occupations that have something to do with construction, such as diverse craft unions; and many interest groups and coalitions that have stakes in the development of construction technology. For example, in the early twentieth century, there was a pressure group formed by rural landowners whose desire to build cheap cottages for labourers was threatened by the building codes (Harper, 1985).

The dynamics and friction among these actors that slow the rate of adoption of new construction technology are too complex to measure in quantitative terms. However, it is useful to single out some strong actors for detailed analysis. Two of the most frequently blamed elements of the locked system are local governments that enforce obsolete building codes, and labour unions.

Building codes. Building code changes should provide good insights for the students of construction technology since these changes reflect technological changes in the construction industry. Strassmann (1978) identified some principles of building code change:

> At around 1800, restrictive building codes and trade unions did *not* come into existence. . . . As a result experimenting was easy, and major and minor catastrophes followed – usually at the expense of others, often insurance companies. Failures naturally led to further research, experiments, and theories. Resulting knowledge was often converted into standardized tables of correct practice for a kind of self-policing. Building codes are these formulations turned into laws, often written under pressure from insurance companies. . . . American [building] codes [governing the use of reinforced concrete] acquired their ultraconservative characteristics after the collapse of an eight-story hotel at Benton Harbor, Mich., in the course of construction in 1924 (p. 267).

Consequently, building codes regulate the technology of construction, and they often delay technological change in construction. 'There is a single gate through which every technological innovation affecting public health and safety must pass if it is to be legitimately employed in the industry: the building regulatory agencies of state and local governments' (Ventre, 1979, p. 56). There are two problems regarding this gate of building codes: building code changes are so infrequent that it is difficult to introduce new construction materials; and the proliferation of building codes leads to regionalism in construction.

Since the gate is formulated according to the acceptable standards of construction that are inevitably based on past methods and materials, the introduction of new construction materials always draws attention. Thus, in many cases, it is necessary to reform the gate before or during the introduction of new technology. However, to be amended, this gate of building codes must pass through another narrow gate – local politics. But, it is not easy to change the 'system' that includes, among others, subcontractors, who are usually strong in the local politics and in favour of the status quo; labour unions that usually try to prevent the introduction of labour-saving technologies; and local bureaucracy that is conservative in nature as far as public safety and public health are concerned.

Labour unions. In construction, due to the high degree of unionization, the labour unions' influence in restricting the introduction of new materials and methods has been more powerful than the unions in other industries. 'It is not uncommon, when a new labour-saving material or method is introduced by a contractor, for a union to demand payment of wages on the labour hours saved. Such practices have discouraged innovation in contract construction' (Cassimatis, 1969, p. 121). Also, the existence of a large number of crafts, each of which acts independently of the others and may have conflicting goals, makes the whole system more complex and discourages the introduction of innovations that would involve several craft unions.

Efforts to unlock the system

Blaming the building codes and unions for their negative roles in advancing construction technology may be scapegoating. There are numerous actors other than building codes and labour unions, and the complex dynamics among them should not be ignored. Ventre (1979) describes this locked system very well:

> A more useful formulation of industry's dynamic can be drawn by analogy with other systems in which power and responsibility are dispersed among large numbers of actors, no one of which has more than a small fraction of the system as a whole. Our analogy is with democratic, multifaceted political systems, where hesitation in the face of technological innovation proliferates through the whole (pp. 57–8).

Many types of construction failures have given the public and the government the power to restrict architectural creativity, material use, and construction methods. The labour movement has given labour unions the power to limit the use of labour-saving technologies. Local politics has given local subcontractors, who are mostly small and most vulnerable to the technological changes, the opportunity for political pressure to keep the status quo. Complaints from users about relatively high construction cost have given some contractors' and architects' groups a chance to raise their voices to point out the technologically restrictive building codes. All these exogenous factors influence the way the system is going.

Therefore, identifying the power level of each actor and the external factors that influence this power level is the key to understanding the dynamics of this locked system. The consequences of these dynamics vary from exceptionally rapid acceptance of an innovation by the 'system', to a stubborn resistance to any changes. After studying some examples of diffusion in the construction industry, Ventre found two exceptional acceptances: non-metallic-sheathed cable owing to World War II materials shortages; and plastic pipe due to the coordinated lobbying efforts of a coalition, the Plastic Pipe Institute. Thus he concluded that 'strong as the homeostatic properties of the building enterprise are, the system *does* respond to external perturbations, particularly to positive pressures for technical innovations. The system is notably indifferent to externally mobilized resistance to change' (Ventre, 1979, p. 58).

Separation of design from production

Another permanent barrier caused by specialization is the separation of design from construction. Whereas product design is becoming an integral part of production management in manufacturing, in construction product design is often completely separated from production management. The consequences of separating design and production have significant effects on the use and development of construction technology.

Fear of introducing new technology. To provide the owners maximum benefit from contractors' price competition, the designer usually considers the prevailing construction practices in the design and avoids setting specific methods that may benefit particular contractors. The obvious consequences of these practices are that the designer is reluctant to introduce new construction materials and methods, fearing the contractors will either refrain from bidding or bid high prices (Cassimatis, 1969). Thus the prevailing construction process technology is one of the forces that oftentimes restrict product innovation by the designer. He cannot easily exert his influence to change process technology and support product innovation.

Lack of cooperation. A designer is usually selected by the owner on the basis of his professional reputation. Designers are often forbidden by their professional associations from engaging in price competition for their services. For example, the American Institute of Architects' Standards of Ethical Practice prohibits members from entering competitions (Sweet, 1977). The actual construction of a building is performed by the general contractor, who is usually selected through price competition. Once the contract is awarded on fixed-price basis, there is little incentive for the contractor to improve the quality of the product. He may have incentives to decrease the cost of production by employing innovative methods or equipment.

The two entities are living in different worlds: the designer's world of reputation, and the contractor's world of price competition and cost reduction. This irreconcilability of the goals between these two entities inevitably leads to a lack of cooperation between the designer and the producer. New ideas in design can be introduced oftentimes with new materials or methods of construction. Continued coordination between these two occupations in the whole process is difficult. This helps make a potentially dynamic industry technologically rigid.

Efforts to overcome. Some solutions have been suggested, such as the use of negotiated contracts, professional construction management methods (Barrie and Paulson, 1978), and constructibility improvement programmes (Tatum *et al.*, 1985). These arrangements are an effort to integrate design and production by promoting the exchange of information. However, there are no quantitative data available to convince the owners to take these suggestions and relinquish the possible benefits of a competitive system. Whether the possible advantages of promoting cooperation between the designer and the contractor, especially in the case of a negotiated contract approach, outweigh the advantages of competitive bidding remains an open question (Cassimatis, 1969).

Directions in developing construction technology

Having described the characteristics of constructed products and the technological constraints inherent in them, we raise an important question concerning the direction of inventive activity in construction. The direction may take on a variety of dimensions. For example, there is a distinction between inventive activity that is directed toward product improvement (product innovation) and inventive activity that is process innovation. Also the direction of technological change is not only responsive to market demands but also shaped by the technology available. In other words, the allocation of resources to inventive activity is generally determined by demand-side forces as well as by supply-side factors.

There is little background research concerning the direction of inventive activity in construction. The Business Roundtable (1982a) found, through surveys and interviews with construction field personnel regarding their needs for technology, that three areas of construction had the highest potential for gains from technological research: piping, electrical work, and installation of mechanical equipment. They tried to entice inventive activities in construction by showing great demand-side forces in markets.

On the other hand, supply-side factors in determining the direction of technological advancement in construction were mentioned, for example, by Moavenzadeh (1985). He advocated a high-technology revolution to restore the troubled construction industry. Though he did not make it clear what specific technology the future market for new construction will need to have, he argued that several promising technologies, for example, computers, robotics, and advanced materials, were standing ready.

Despite all these existing demand-side factors and abundant supply-side factors, which are the two essential forces sufficient to spur inventive activities in other industries, it still seems that there has been little inventive effort to advance construction technology. Also the amount of R & D effort in construction is still negligible (National Research Council, 1986).

We agree that it is important to study demand-side factors and supply-side factors that generally shape the direction of inventive activity. Nevertheless, we argue that it is important to recognize the premise under which those general rules and theories are formed. The premise is that there are no particular technological constraints on the application of those theories; many people have failed to recognize the unique characteristics of constructed products and the technological restrictions inherent in them.

We point out that it is important to recognize the unique technological restrictions of construction and to allocate resources to overcome these fundamental technological restrictions. We believe that it is time, after seeing the ineffectiveness of focusing on the short term, to think about the long-term goals of advancing construction technology under a premise that the restrictive characteristics of the constructed products could be changed and eventually removed. Paradoxically speaking, we argue that *construction's* long-term goals regarding its technology are *not* to be *construction* as traditionally defined by the characteristics of its products – immobility, durability, etc.

By this we are not suggesting a revolution in a short-term perspective. Rather, what we are proposing is a long-term destination. Then the allocation of resources to inventive activity can be directed towards creatively destroying the characteristics of constructed products, and accordingly the technological constraints in construction. The long-term goals include: overcoming immobility (modularization is an example); finding ways to handle complexity; replacing heavy and bulky materials; decreasing the costliness of constructed products; and developing some means to lessen the burden of social responsibility. These goals are a great challenge, but also paths (and perhaps the only ones) to major technological advancement in construction.

Practical applications

Immobility, complexity, durability, costliness, and social responsibility, the characteristics of constructed products described in this paper, create several problems and opportunities. At least two of the problems, limited use of mass production and separation of design from production, offer important opportunities for practical application and competitive advantage.

Both researchers and industry professionals are currently seeking ways to automate appropriate construction operations. The characteristics of constructed products identified in this paper suggest that these efforts will be more successful if they take a broader view. Greater mass production of constructed products may require both different designs and different work locations. A broader view of the overall process of design, fabrication and construction could produce some important advantages for firms seeking to develop and exploit new construction technology.

The traditional separation of design and production also offers an important opportunity for improvement. Product and process innovation appear strongly related in construction. Firms that increase the degree of integration between design and construction can develop new technology and gain competitive advantages based on it.

Needs for future research

The scope of this paper was limited to recognizing the peculiar characteristics of constructed products in an attempt to understand the resulting limitations of construction technology and to review the effort to overcome these limitations. This description largely excluded forces for change in the construction industry. Thus, a major opportunity for additional investigation rests in understanding the dynamics of the construction industry and the technological restrictions they cause. Specific topics may include contracting arrangements and their consequences for construction technology; the structure of the industry; and the relationship between technological development and changes in demography, mortgage rates, government policy, and economic cycles.

The differences between the construction industry and manufacturing industry in terms of the technological constraints and technological phenomena identified in this paper suggest that the innovation process will be significantly different in the two industries. Therefore the innovation process in construction merits intensive research. Among many possible investigations regarding the innovation process, the ones with the greatest potential contribution to the technological advancement of construction may be investigations of the process of product innovation and evolutionary innovation.

Research on the diffusion process in construction offers another opportunity to increase understanding of construction technology because adopted innovations appear to play an important role in the technological progress of construction. Many diffusion theories (e.g. psychological model, informationally constrained model, equilibrium model, path-dependent theory) or organizational theories (e.g. bounded rationality) suggest fundamental questions regarding the differences in the process of innovation in the differing context of the construction industry.

The study of differences in constructed products and construction technology suggests another area of investigation. How do (or should) construction companies shape their strategies to increase the rate of innovation or adoption, and to gain competitive advantages? The Business Roundtable found that managers in construction often do not perceive investment in better construction technology as feasible or likely to help their competitive position. Why not?

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