Classification System for Construction Technology

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Abstract: Better understanding of the components of construction technology and the ways in which they differ for different construction operations will support technological advancement and improve the competitiveness of the U.S. construction industry. This paper describes a classification system that includes the following components: material and equipment resources, construction-applied resources, construction processes, and project requirements and constraints. The elements and the attributes of the classification provide a tool to measure technological change and analyze specific operations for potential improvement. The paper reviews the relevant background, develops the classification system, describes its use to define the technology for specific construction operations, and highlights conclusions regarding the components of construction technology and the potential for future use of the classification in both research and construction practice.

Introduction

Is the U.S. construction industry in desperate need of new technology to increase competitiveness? Or have the complexity and diversity of construction technology masked steady advances? How can firms become more innovative and gain competitive advantages based on advanced construction technology? To assist in answering these critical questions, we need to understand better what construction technology is. This requires a measurement tool and a way to systematically analyze the technology for specific construction operations. This increased understanding of construction technology should help identify opportunities for improvement and assist firms seeking competitive advantages based on advanced technology. But the complexity and diversity of construction operations make the task of classifying construction technology a difficult one. This paper describes a first attempt.

A general definition summarizes the classification. In this paper construction technology is defined as the combination of resources, processes, and conditions that produce a constructed product. A resource can be either materials and permanent equipment (e.g., a steel beam or an elevator) or construction applied (e.g., bricklaying skills or construction equipment). Construction processes are the methods and the tasks needed to build a constructed product. Project requirements and site characteristics are the major conditions of construction technology.

The purpose of this paper is to describe a classification system for construction technology, to suggest possible applications of this system in research and practice, and to develop conclusions concerning the nature of construction technology and the implications of its differences. It summa-

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rizes the results of an exploratory research project that sought: (1) To identify basic variables describing construction technology and understand fundamental relationships between these variables; (2) to develop a conceptual framework for construction technology; (3) to support investigations of technological advancement; and (4) to provide a basis to develop new tools for construction analysis and planning (Tatum 1987a; Tatum and Nam 1988). This project is part of an ongoing investigation of mechanisms and strategies for technological advancement in construction (Nam 1987; Tatum 1986a, Tatum 1986b).

The classification developed in this research provides a conceptual framework to capture the diverse elements and analyze the technology for major types of construction operations, such as structural steel erection, pipe welding, or cable pulling. It also includes elements that recognize the differences in conditions on individual projects. Future investigations will involve testing and refinement of the classification by application to more specific operations and project conditions.

The conceptual framework of the classification has proven to be a useful tool in studies of specific construction innovations (Tatum 1986b). The components have provided a broad classification for the selection of innovations to include in the study group. The system assists in grouping innovations by industry segment and type. The components of the classification system give a more detailed tool for the measurement of technological change. Also, classifying many construction operations using the system and searching for needed improvements can highlight the potential application of new technologies from other industries to construction.

The paper begins by briefly reviewing the background research from construction and other fields. It then develops a classification system for construction technology, describes it use, and highlights conclusions and practical applications. The development of the classification system involves identifying and describing the four components of construction technology and the elements that make up each component.

Background Research

This section reviews prior investigations of construction and manufacturing technology and illustrates the need for greater understanding of the components. An unresolved debate illustrates the fundamentally different views of construction technology: do construction firms offer a product or do they offer a service ("Not a service industry," 1983; Rogers 1984)? Several investigators have highlighted differences between construction and manufacturing. Examples include: risk and uncertainty of operations (Ashley 1980; Ashley and Tucker 1984), high levels of variation in work environment (Paulson 1985), differences in the potential for capital/labor substitution (Koch and Moavenzadeh 1979), diversity of work operations, highly variable work environment, frequent interdependency of activities, and changing access to the workface.

Priorities for Technological Advancement in Construction

A study for the Business Roundtable (*Construction technology* 1982; Tucker 1982) used 15 indicators for work difficulty for 17 construction activities in a survey to determine opportunities for improvement of

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Hierarchical Level	Description and Basic Focus
Organizational	Company structure and business focus. Head office and field functions. Gross project attributes: total cost, duration, profit.
Project	Project definition, contract, drawings, specifications. Product definition and breakdown into project activities. Cost, time, and resource control focus.
Activity	Attainment of physical segment of the project. Current cost, time, and resource use. Status focus.
Operation	Construction method focus. Means of achieving construction. Complete itemized resource list. Synthesis of work processes.
Process	Basic technological sequence focus. Logical collection of work tasks. Individual and mixed trade actions. Recognizable portion of construction operation.
Work task	Fundamental field action and work unit focus. Intrinisic knowledge and skill at crew member level. Basis of work assignment to labor.

Source: Halpin and Woodhead (1976)

FIG. 1. Hierarchical Levels in Construction Management

construction technology. These indicators included requirements for various types of resources (e.g., crafts, specialized tools and equipment), the potential for specific problems (cost, schedule, rework), constraints on field operations (sensitivity to quality of design, sensitivity to prefabrication accuracy), productivity impacts (wasted time, number of different crafts required), and management requirements (communication, coordination). With these indicators, this classification effort focused on identifying advances in construction technology that would improve productivity (Tucker 1982).

Construction Simulation

Halpin and Woodhead (1976) provided an early framework for analysis, design, and simulation of construction and process operations. Their classification of construction included: (1) Structure or finished product, such as power plant or bridge; (2) material used in the construction operation, such as concrete or piping; and (3) function, such as welding or framing. This broad structure of construction operations fits within the six hierarchical levels shown by Fig. 1. These authors defined a construction operation "as a collection of work tasks and processes embodying the commitment of resources within a technological format or methodology that leads to the placement of construction." (Halpin and Woodhead 1976, p. 5) They suggest characterization of construction operations by technology, by resource use, and by breakdown into work task and sequences. A task is focused at the level of field actions and the field work unit. In the construction hierarchy of this model, the activity level provides adequate information for management needs, but analysis and planning at the process and work task levels are essential for resource distribution at the site. Existing modeling concepts, as judged by these authors, did not provide adequate representation of the complexity and interaction of

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construction operations. To satisfy this need, Halpin developed the CYCLONE model (Halpin 1977). This system uses graphical elements to model the action and idle states of construction resources on specific projects. Paulson and other researchers at Stanford modified and supplemented the CYCLONE simulation in search of economical means for field data acquisition, data reduction and analysis, and graphical simulation of construction operations (Paulson et al. 1983; Paulson et al. 1987).

Construction Methods and Productivity Improvement

Parker and Oglesby (1972) provided an early analysis of construction planning and operations using industrial engineering tools. To improve methods and efficiency in construction, they recommended activity or work sampling, photographic or other methods of data collection, and analysis using crew balance studies, flow diagrams, and process charts. This early set of analytical tools focused on construction operations and considered the influences of the technologies required for their completion. In a more recent model of the construction process developed for productivity improvement programs, Howell and Kasten identified six resource requirements (place, materials, tools, energy, people, and information) as essential inputs to the methods to achieve a desired construction product (Howell and Casten 1983). Further work in the design of control systems for productivity improvement (Sanvido 1984) resulted in a model of construction as a dynamic system. Major elements of the model include inputs, outputs, conversion processes, and a controller. The model also considers influences on the supply of resources, influences on planning, and influences of the project on participants and the environment.

Manufacturing Operations

Hayes and Wheelwright (1984), following Armstead et al. (1977), developed a technical classification of manufacturing processes. This included major categories of processes for: (1) Changing physical properties; (2) changing the shape of materials; (3) machining parts to a fixed dimension; (4) obtaining a surface finish; and (5) joining parts or materials. They also identified three differing perspectives on technology: those of the technical specialist, the operations manager, and the general manager. Schmenner (1981) identified five fundamental types of production processes: job shop, batch flow, worker-paced assembly line, machine-paced assembly line, and continuous flow. The variables Schmenner used to differentiate these processes included product features, process features, materials-oriented features, information-oriented features, labor-oriented features, and management features.

Economics and Organization Theory

Rosenberg has argued persuasively that to study productivity and other issues important to economists adequately it is necessary "to break open and to examine the contents of the black box into which technological change has been consigned by economists" (Rosenberg 1982, p. vii). He concludes that we have consistently done a poor job of anticipating the effects of technological change because we are dealing with an extraordinarily complex and interdependent set of relationships (Rosenberg 1986).

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Gold et al. (1980), conducted a long-term, NSF-supported investigation to develop and test a model for analyzing the effects of major technological innovation in industry. This research identified several problems with the current means of evaluating technological innovations. These methods focus on capital budgeting, using such techniques as return-on-investment and net-present value. Gold suggested a revised framework to measure technological changes and their effects, including both physical flow effects and cost effects. This framework includes categories for: (1) Modifications in the physical and chemical properties of material inputs; (2) changes in the design and scale of processes or facilities; (3) improvements in control systems; and (4) alterations in the design of products.

Investigators of organizations have also found it necessary to develop classification systems for technology. These systems use three critical variables: complexity, uncertainty, and interdependency (Scott 1981). Complexity refers to the number of different items or elements that must be dealt with simultaneously by the organization. Uncertainty refers to the variability of the items upon which the work is performed. Interdependence indicates the extent to which work elements or processes are interrelated so that changes in the state of one may affect the state of the others. Thompson (1967) characterized interdependency as pooled (work contributes to a common goal), sequential (time dependent sequence) or reciprocal (activities relate as both inputs and outputs), and identified differing coordination requirements for each. Galbraith (1977) suggested that information processing requirements, as determined by the level of uncertainty, further classify work technology.

Conclusions from Background Research

These prior investigations of technology in many fields produced findings that guided the research described in this paper. First, there is a strong need to analyze and classify technology as a basis for research in such diverse fields as construction, manufacturing, economics, and organization. Second, existing classifications do not fully capture all components generally included in definitions of construction technology: construction methods, construction processes, construction equipment, and materials of construction (*Construction R&D* 1981). Third, the investigations of technological advancement in construction and of construction simulation have each included a classification to support the specific research need. However, the development of a conceptual framework for construction technology remains an important research task.

Overview of Classification System

To describe construction technology and attempt to capture its complexity, the classification system developed in this research includes a hierarchy of four parts: components, elements, attributes, and values (see Fig. 2).

1. The components include: material and permanent equipment resources—the materials and equipment specified by the designers and permanently incorporated into the constructed product; construction-applied resources—what construction adds to increase the value of materials and equipment in producing the constructed product; construction

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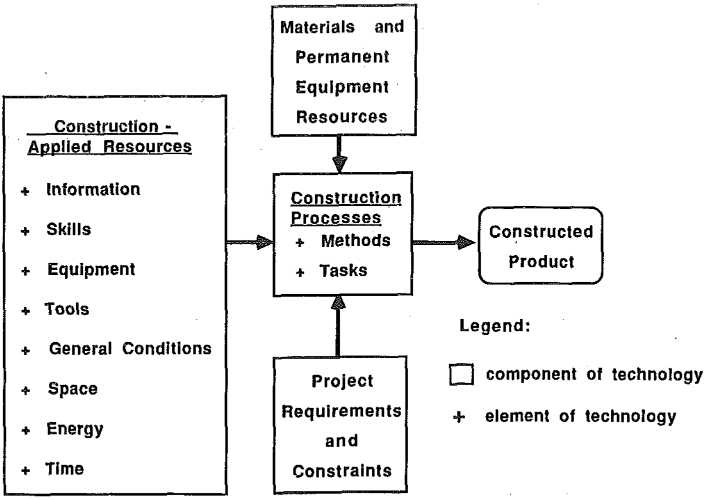

FIG. 2. Overview of Classification System for Construction Technology

processes—the way in which applied resources transform material and permanent equipment resources into constructed products, including both construction methods and construction tasks; and project requirements and constraints—the unique conditions which strongly influence the selection of both construction-applied resources and construction processes.

2. Two of the components (construction-applied resources and construction processes) contain several elements. These are types of resources (e.g., tools or energy) or parts of processes (e.g., methods or tasks).

3. Several attributes define each of the elements. These are the characteristics that differentiate the technology for separate operations. There is a definition for each; see Fig. 3 and the following sections for examples.

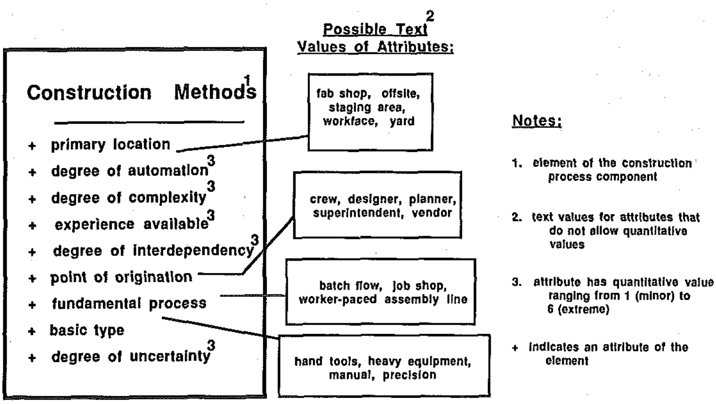

FIG. 3. Example of Element, Attribute, and Value

4. The values for these attributes, as illustrated in Fig. 3, may give a rating on a scale, identify a class or type, or further describe the element. The rating system used for all values that could be quantified was a scale ranging from 1 (minor) to 6 (extreme).

Research Method

The development of the system was an exploratory effort to investigate the possibility of classifying construction technology. The classification was developed by considering the background research and selecting elements and attributes that appeared to describe construction technology and to allow generalization over differing types of operations. The research continued by refining the attributes many times as a result of applying them to specific construction operations. It should be noted that this investigation did not include testing the classification with data from actual projects—a necessary area for further research. The criteria for selecting the elements and attributes were the ability to capture the factors that bring about the changes in technology and the potential importance in improving productivity.

The values of attributes for specific operations were selected for general applicability over a range of project conditions. Although these values do not characterize a specific technology on a specific project, they assisted in testing and refining the classification. This application to 14 different construction operations, such as concrete transport and electrical cable pulling, also resulted in several insights regarding the differences in technologies for differing operations and the need to detail the classification further to capture these differences adequately. These are highlighted in the conclusions. Both the report of this research (Tatum 1987b) and the database developed for the classification specify the possible values for each attribute. The following sections of this paper identify the elements and attributes for each component of construction technology.

The researchers used commercial database software (*R:Base* 1986) as a tool to incorporate the elements and attributes of the classification, to allow application to differing operations, and to facilitate analysis of the technology for an operation or comparison between operations. This unusual application of microcomputer-based database software is described elsewhere (Tatum 1987). The database and documentation are available at reproduction cost from the writer.

It is very difficult to describe a classification system designed to function as an interactive tool in a technical paper. This system has 4 components, 10 elements, 53 attributes, and many different types of values for each attribute. The following sections of this paper describe each of the components, identifying all elements and attributes. The description also includes an indication of which attributes have quantitative values [they are marked with the notation "(numerical scale)"] and gives example values for those that are not quantitative [indicated as "(e.g., . . .)"]. See the user's manual (Tatum 1987a) for a full listing of possible values and examples of applying the classification to several different types of construction operations.

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Materials and Permanent Equipment Resources: First Component

It is well recognized that the quantities of major construction materials (e.g., cubic yards of concrete or lineal feet of piping) and the permanent equipment (e.g., elevators or boilers) define the scope of a project. But the key role of construction materials in construction technology is less obvious. For example, the technologies for constructing structural steel and reinforced concrete structures differ significantly. Many attributes of materials and permanent equipment have important implications for construction technology; they provide restraints for planning and construction operations. The following attributes describe the materials and permanent equipment resource component of construction technology in this classification system:

1. Degree of precision required in maintaining dimensional tolerances during fabrication and installation (numerical scale).
2. Degree of engineering and detailing required (e.g., bulk, standard, or engineered materials) to define the material for use in the operation.
3. Identification of the major materials required to complete the operation (e.g., architectural, civil, electrical, mechanical, structural, or thermal).
4. Most likely leadtime from order placement to delivery for the primary materials category required to complete the operation (numerical scale).
5. Degree of restrictions on construction operations posed by the material (numerical scale).
6. Key physical property of the primary material that influences the construction operation (e.g., abrasion resistance, compaction, conductivity, ductility, hardness, strength, weight, or workability).
7. Primary materials category (e.g., architectural, building, civil, electrical, HVAC, instrumentation, mechanical, piping, structural, thermal).

Construction-Applied Resources: Second Component

Applied resources are what construction adds to increase the value of materials and permanent equipment in producing a constructed product. Although often less visible than materials and permanent equipment, resources applied by construction are perhaps more fundamental in defining a construction technology. The concept of applied resources and differences in the point of application is useful in studying alternate methods, such as preassembly and modularization (Williams 1987). In this classification, construction-applied resources consist of eight elements: information, skills, equipment, tools, general conditions, space, energy, and time.

The eight elements of applied resources can take many forms: data or knowledge (information and skills); physical (equipment, tools, parts of general conditions, and space); services (parts of general conditions); energy input; or time allowed. Information defines both the "what" and the "how" of construction technology. Skills enable it to happen. Construction equipment is the means to mechanize (and possibly automate) construction operations. Tools are hand instruments that assist in performing construction tasks. The general conditions and space are the site-related applied resources. Energy is consumed in producing the con-

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structed product. The time allocated to specific operations stems from their scope and importance. Each of these forms of applied resources is discussed in the following sections.

Information

Information provides the fundamental definition of design and construction requirements and therefore sets the choice for all other resources. A second key role of information in construction technology is the coordination of operations. Information also captures the experience-based knowledge regarding each operation. The following attributes describe the information element of construction-applied resources:

1. Major information required for coordination (e.g., fabrication, operations, progress, or specifications).
2. Degree of information required to define and perform the construction operation (numerical scale).
3. Major type of construction information required to plan, select methods for, define, and execute the operation (e.g., constraints, method, workface).
4. Degree of influence by drawings, physical configuration, and weight requirements on the selection of methods and the performance of tasks for the operation (numerical scale).
5. Other type of design information or requirement that defines or influences the methods and tasks required for the operation (e.g., code, configuration, performance, routing).
6. Degree of design information required to define the construction method and perform the work operation (numerical scale).
7. Degree of influence by the specification and performance requirements on the selection of methods and on performing tasks for the operation (numerical scale)

Skills

Skills are often a key applied resource in efficiently performing a construction operation. This element focuses on craft and supervisory skills because they are closest to performing the work. The following attributes describe the skills element of construction-applied resources:

1. Craft component or degree of craft skill required to successfully complete the construction operation (numerical scale).
2. Essential craft skills needed to acceptably complete the construction operation (e.g., operate specialized equipment or weld).
3. Manual labor component or degree of manual labor required (numerical scale).
4. Essential supervisory skill needed to oversee the work (e.g., coordination or technical).
5. Supervision component or degree of supervisory involvement necessary to plan, direct, and review the construction operation (numerical scale).

Equipment

Several factors make construction equipment a key element of construction technology. The type of equipment and extent of equipment use

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determine the degree of mechanization and automation used for an operation. Equipment is expensive. It introduces new limitations, such as access requirements or maximum allowable loading on a foundation. The following attributes describe the equipment element of construction-applied resources: (1) Amount of equipment use in the construction operation (numerical scale); (2) primary equipment type required to perform the operation (e.g., earthmoving, handling, machine, transporting, welding); (3) specific equipment item required, based on the primary equipment type (e.g., backhoe, crane, or scraper for earthmoving); and (4) degree of conformance to industry standard equipment requirements and availability (numerical scale).

Tools

Tools are generally less expensive than equipment and require greater human effort to use, but disparate and dispersed construction operations make tools important. Large productivity changes can come from small but clever tools. The following attributes describe the tools element of construction-applied resources: (1) Amount of tool use in the construction operation (numerical scale); (2) degree of conformance to industry standard tool requirements (numerical scale); and (3) major type of tools needed to complete the construction operations (e.g., align, measure, power, test).

General Conditions

General conditions are the facilities and services required to support efficient construction operations. When available, they do not seem to be an important element of construction technology. But when, for example, protection from weather, necessary utilities, or proper safety equipment are not available, construction operations are severely affected. The following attributes describe the general conditions element of construction-applied resources: (1) Special buildings or facilities required to complete the operation (e.g., assembly, maintenance, storage); (2) special services required to complete the operation (e.g., calibration, maintenance, security); and (3) special systems required to complete the operation (e.g., communications, dewatering, power).

Space

The absence of adequate space can be a critical constraint on construction operations. Space availability determines the use of other applied resources, such as large equipment, and heavily influences the efficiency of construction operations. The following attributes describe the space element of construction-applied resources: (1) Space component or importance of space and access in completing the operation (numerical scale); (2) degree of difficulty or constraints for material access to the workface (numerical scale); and (3) degree of difficulty or constraints for personnel access to the workface (numerical scale).

Energy

The energy element of applied resources relates to the degree of mechanization of the construction operation. Some operations are energy intensive; others are manual. The following attributes describe the energy element of construction-applied resources: (1) Amount of energy use in completing the construction operation (numerical scale); and (2) primary energy type required for the construction operation (e.g., chemical, electric, mechanical).

Time

Alternate technologies differ in the time required to complete construction operations. The following attributes describe the time element of construction-applied resources: (1) Time component or normal importance of the expected completion of the operation (numerical scale); and (2) timing relationships with other activities to complete the construction operation (e.g., coordinated, independent, reciprocal).

Thus far, the writer has described two types of resources that are key components of the technologies for construction operations: materials and permanent equipment, and construction-applied resources. Construction processes and project requirements, described in the next two sections, complete the four components of construction technology.

Construction Processes: Third Component

Construction processes define the way in which applied resources transform material and permanent equipment resources into constructed products. They are the focus of attempts to advance construction technology and increase productivity through methods improvement. Unlike manufacturing, construction processes are always changing—in response to both changing design requirements and working conditions. In this classification, construction processes include two elements: construction methods and construction tasks.

Construction Methods

Construction methods are the means used to transform resources into constructed products. They define how construction applies resources. The following attributes describe the construction methods element of construction processes:

1. Degree of automation currently involved in the use of the method, as indicated by the number of specific tasks completed without human intervention (numerical scale).
2. Degree of complexity involved in operations employing the method, as indicated by the number of differing tasks involved (numerical scale).
3. Experience available for use of the method to complete the specific operation (numerical scale).
4. Degree of interdependency involved in the use of the method as indicated by the number of relationships with other operations (numerical scale).
5. Primary location of the construction operation involving the method (e.g., fabrication shop, off-site, staging area, workface, or yard).
6. Point of origin or choice of the method (e.g., crew, designer, planner, superintendent, or vendor).
7. Fundamental process involved in the method (e.g., batch flow, continuous flow, job shop, machine-paced assembly line, or worker-paced assembly line).

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8. Basic type of construction method used (e.g., hand tools, heavy equipment, light equipment, manual, power tools, or precision).
9. Degree of uncertainty as indicated by the inability to predict the results, such as quality, timing, or cost (numerical scale).

Construction Tasks

The tasks needed to perform the construction operations have attributes that are important for the technology. As discussed earlier, tasks differ from operations and processes because tasks focus on field action and the work unit. The following attributes describe the construction tasks element of construction processes: (1) Task difficulty as indicated by size, precision, or special requirements (numerical scale); (2) task interdependency as indicated by the degree to which one task affects others in completing the construction operation (numerical scale); (3) primary task type (e.g., connect, erect, fabricate, handle, install, machine, produce, prepare, test); and (4) secondary task type, based on the primary task (e.g., for fabricate: assemble, bend, cut, grind, punch).

Project Requirements and Constraints: Fourth Component

Of the construction technologies for an operation available in the industry, only a limited number may fit within the constraints for use on a specific project. Many influences form the constraints that create the project conditions, such as: project objectives, regulatory requirements, contractor's capabilities, and area resource availability and practices. The following attributes describe the project requirements and constraints component: (1) Degree of influence by the project organization environment on the selection of methods and the performance of operations (numerical scale); (2) major external influences in the project organizational environment (e.g., competitor, governmental, supplier); (3) degree of influence by the project site on the selection of methods and the performance of operations (numerical scale); and (4) unique site conditions that influence the selection of methods and the performance of operations (e.g., altitude, drainage, soil).

Using and Further Developing Classification System

Defining the components, elements and attributes, as described in this paper, as a part of building the classification system provided some useful insights regarding technological structure. In this step the researchers identified the elements and attributes, prepared definitions for each attribute, and developed a preliminary list of possible values. These were first prepared as lists that became appendices to the research report and were later loaded into the database software as allowable input values for the columns of the relational database. The research then involved three additional steps described in this section: applying the classification to construction operations from each of the major types of construction; using the system to compare construction operations; and using the classification as a research tool. This section also describes needs for further development of the classification system.

TABLE 1. Example of Database Structure

	Materials and permanent equipment resources		APPLIED RESOURCES			CONSTRUCTION PROCESSES		Project Requirements and Constraints
			Information	Equipment	Space	Construction methods	Construction tasks	
Construction *operation* (1)	Degree of engineering and *detailing* (2)	Restriction on operations by *material* (3)	Major type of construction *information* (4)	Primary equipment *ment type* (5)	Space com*ponent* (6)	Degree of *complexity* (7)	Primary task *type* (8)	Unique site condi*tions* (9)
Pipe erection	5[a]	5	sequence	erecting	5	5	Install	none
HVAC ductwork	5	5	procedure	lifting	5	4	erect	none
Concrete formwork	5	5	schedules	erecting	5	4	erect	none
Mechanical equipment alignment	6	5	procedure	connecting	5	5	Install	none
Site earthwork	1	3	constraints	earth-moving	5	4	handle	all

[a]On a scale ranging from 1 (minor) to 6 (extreme).

Application to Construction Operations

Applying this structure to specific construction operations indicated the need for many additions and refinements. This step involved selecting representative construction operations, selecting values for each of the attributes for the operation, and entering the values in the database. The operation became the row of the database and the value (integer or text) became the data stored in the cell formed by the attribute (column) and the operation (row). See Table 1 for an example of the database format.

The following categories of construction and the specific construction operations were selected for this initial application of the classification system:

1. Architectural construction: exterior wall installation.
2. Building construction: heating, ventilating, and air conditioning (HVAC) ductwork; HVAC equipment installation.
3. Structural construction: concrete formwork; concrete transport; structural steel erection.
4. Electrical construction: electrical cable pulling; electrical raceway erection.
5. Mechanical construction: mechanical equipment alignment; piping erection; piping welding.
6. Civil construction: site drainage; site earthwork; pile driving.

The database implementation of the classification provides a table of allowable values for the user as a part of the input forms. The software also checks to assure that the values specified for any operation are from the list of allowable values. The report of this research project (Tatum 1986a) includes a definition of each operation and the values selected for each attribute. This application to several construction operations demonstrated both the value of systematically analyzing the technology for a construction operation using a classification system and the difficulty of assigning values for specific operations. These are both discussed in the conclusions section.

Comparing Within and Between Operations

The database implementation of the classification allows several uses that make the system a flexible tool for analysis of specific construction operations or comparison between various operations. This supports the goals of this research: to develop a tool for measuring changes in construction technology and to identify opportunities for improvement. The following types of searches in the database illustrate this: (1) The user selects values for one or more attributes and queries the database to find all operations that are less than or greater than this reference, such as: find all of the operations for which the degree of conformance to industry standard equipment is high (value or the numerical scale equal to 5); or find all operations for which the point of origin of construction methods is the designer; (2) compare two specific operations, such as: find all of the attributes of structural steel erection that have a value greater than the value of the corresponding attribute for concrete transport; (3) identify all the operations that use a specific resource (such as vendor's design information or backhoes) or have a certain characteristic (such as high degree of construction information required); and (4) identify all of the operations which have a particular set of values for several attributes, such as: operations with low (indicated by value less than or equal to 2) equipment intensity, high (greater than or equal to 4) degree of influence by physical configuration, and point of choice of the method by the crew.

Using Classification as Research Tool

The classification system for construction technology has proven to be a useful tool in an ongoing investigation of mechanisms for technological innovation in construction in three ways (Tatum 1986b). First, the elements have provided a broad classification for the selection of innovations to include in the study group. The system assists in grouping innovations by industry segment and type. For example, we have equipment innovations in heavy and industrial construction, materials innovations in building construction, and methods innovations in heavy and building construction.

Second, the attributes in the classification system give a more detailed tool for the measurement of technological change. This more specific definition of innovation type gives greater insight regarding the process. For example, in analyzing an innovation in construction methods, the classification assists in distinguishing among several types: (1) Changes in the degree of automation; (2) changes in the degree of complexity for the method, or increased simplification; (3) changes in the interdependency with other methods, or increased flexibility in the construction method; (4) changes in the location of the work, such as shifting from the workface to the shop or the yard using preassembly or modularization; and (5) changes in the uncertainty involved, such as simplified operations, allowing field adjustment, or using more familiar approaches.

Third, the classification can assist in identifying priorities for the investigation and development of new construction technologies in at least two ways. Setting values for each of the attributes, applying the classification to a number of operations, and searching the database allows identifying specific operations for which the current state of technology gives an opportunity for improvement. For example, the attribute value for an operation (such as pipe welding) may indicate a high level of influence by the specifications in selecting methods and a low level of automation. This condition could indicate the opportunity for using advanced technology to decrease the uncertainty of meeting the specification requirements.

Also, classifying many construction operations using the system and searching for needed improvements can highlight the potential application of new technologies from other industries to construction. For example, several operations with high equipment intensity and high information requirements for coordination could indicate important opportunities for new technologies associated with real time data acquisition and remote process control.

Needs for Further Development

The results of using the classification system in research projects to date suggest needs for further development and use. A key need is to develop criteria and test whether the classification system is better or worse than some other scheme for analyzing construction technology. Possible criteria include: (1) Ability to capture the diversity of construction technology and the numerous alternatives available to perform a specific operation on a project; (2) flexibility to allow application to differing types of construction operations; (3) user interface, ease of use, and operability for analysis of construction operations during project planning; and (4) value as a research tool as indicated by ability to identify and classify changes in construction technology during investigations of the process of innovation.

Further development of the classification also requires using it to handle the situation in which different methods to perform a particular construction operation have different attribute values. For example, concrete transportation by pumping and by conveyors would require different values of the attributes for equipment, general conditions, space, construction methods, and construction tasks. The current structure of the classification allows the use of multiple methods by coding the operations as a separate line in the database. However, the development to date did not include coding two different methods for the same operation. This additional step may indicate the need for changes in the classification system to accommodate multiple methods for the same operation.

The development of a classification system for construction technology in this investigation points out other needs for additional research. The classification now demonstrates the feasibility of developing a conceptual framework, but realizing the potential benefits will require a more detailed system, applied to construction operations on specific projects. This application and further testing will provide the experience necessary to refine the classification further. Refinement of the classification would result from both applying it to a broader range of related operations, such as by adding concrete finishing and various types of operations to connect piping, and by applying the classification to a specific operation, such as piling installation, at a greater depth and with a focus on more specific methods for completing the operation.

Additional development and use both by researchers and industry professionals will support the tailoring of the classification to specific needs. Researchers could apply the system to assist in setting priorities for both the adoption of available technologies in construction and the development of new technologies for the specific construction operations that offer the greatest potential for improvement. This would also give additional insights regarding the most effective ways to analyze and plan the technologies for a specific project and to consider technology in the strategic planning for a construction firm.

Conclusions and Practical Applications

Both researchers and industry professionals need a classification system or taxonomy to understand, analyze, and improve construction technology. This conceptual framework can help to understand current problems better and assist in setting priorities for advancement of construction technology. In attempting to provide this framework, this investigation led to several insights concerning construction technology, indications of both the value and the limitations of a classification system, and possible practical applications by industry professionals.

Insights Concerning Construction Technology

The efforts to develop an initial framework for the classification of construction technology in this research brought about several insights concerning the structure of construction technology:

1. Materials and permanent equipment resources, which are defined by the design requirements, set the scope of requirements for other resources and the types of construction processes which are feasible for the project.
2. Construction-applied resources are the value that construction operations add to material and permanent equipment resources to produce a constructed product. Some of the applied resources are based on knowledge and experience; others are hardware; still others are based on project requirements and site conditions. All applied resources are scarce and expensive. Effectively managing field construction operations requires sound strategies for the effective use of applied resources.
3. Resources appear to be an essential part of construction technology. They determine the other components. This differs from the traditional view of economists that output is a function of labor, natural resources, capital, and technology.
4. Construction processes involve fundamental methods and the actual tasks to complete construction operations. Both types of resources (materials and construction-applied) influence and even determine construction processes. Conversely, taking advantage of the opportunity to use beneficial construction processes may require changes in one or both types of resources.
5. Project requirements and constraints highlight the need to consider the application in the classification of construction technology. It is possible to consider the state of available technology at the level of the entire industry or the firm, but the actual application of a technology to perform an operation depends heavily on the conditions surrounding its use.

6. The diversity and the interdependency of the elements and attributes that define the technology for a specific construction operation highlight the need to consider all the components and integrate many activities to advance construction technology.

The complexity of the classification system identified in this research also highlights two major conclusions concerning technological advancement in construction. First, with all the variables and influences, there should be many opportunities for improvement. The applied resources and construction processes for specific operations can differ on each project. Indeed, differences in material and permanent equipment resources often force differences in applied resources, in construction processes, or in both. The challenge here appears to be finding a way to take advantage of the assessment of technology forced by the unique requirements of each project and to seek innovation and performance improvement actively. In other words, to avoid blindly applying unit rates and their embedded assumptions.

Second, the complexity and project specificity of construction technology create many hurdles for its advancement. Solving a specific problem, such as the automation of an operation, may advance the technology but may not necessarily contribute to a broader understanding of overall needs and priorities for technical progress in design and construction. Managers for owners, designers, and contractors need to understand better the entire process from feasibility assessment to facility operation, to view the technologies for each major activity as parts of an integrated whole, and to direct efforts to advance construction technology in accordance with this broad perspective.

Value and Limitations of Classification System

The classification system described in this paper is useful as a research tool. In fact, the complexity indicated by the system highlights the need for a tool to allow systematic analysis. The classification allows researchers to make comparisons between elements of construction technology that are not otherwise possible because of the complexity and number of attributes. This allows better understanding of current technologies as well as better focusing of efforts to advance construction technologies. Using a classification system can also assist in education by helping to explain the complexity of construction technology and by pointing out the need for technological innovation to solve specific types of problems. Despite the many useful results of this effort, this investigation also points out limitations of both the attempt to develop a classification of construction technology and the specific system developed. Among these limitations, the following appear most meaningful for future research and for use of a classification of construction technology:

1. Construction technology is very complex—perhaps too complex to capture in a single classification system. Many general descriptions indicate this, but the classification system developed in this research better defines and highlights the sources of this complexity. It identifies the many variables and suggests that an extensive analysis is needed to select the most appropriate technology for a specific operation and set of conditions.

The classification system also points out the difficulty in measuring the state of the art and in generalizing about the state of any specific construction technology.

2. It is possible and useful to identify distinct elements and attributes in a classification system for construction technology, but this effort points out how related each of the attributes are. Efforts to improve the technology by changing one attribute will usually alter others.

3. Selecting values of an attribute for a specific operation highlights the need to define the operation in very specific detail, including both aspects of the operation that would apply in any situation and aspects that relate to application on a project.

4. Quantitative factors, such as degree of equipment use or delivery time, are not adequate to classify construction technology. Both uniquely identified resources and qualitative values of attributes are necessary to capture the complexity of technology for a specific construction operation.

5. Pursuing a level of detail adequate to specify individual operations fully quickly leads to a large classification system. Even with attributes at a detailed level, assigning values often points out the need for a more specific definition.

6. The operations give insights regarding the attributes and possible values and the attributes give insights regarding the operations. The process of assigning values to attribute for specific operations therefore assists in refining the classification system.

Practical Applications by Industry Professionals

Although this research has taken the classification system only to the stage of a conceptual framework, the results indicate the potential to assist industry professionals in making decisions about construction technology at both the level of the project and the firm. The classification system provides a potentially useful tool to assist construction managers in analyzing and planning for specific projects and senior managers in analyzing markets and technologies for potential competitive advantages.

Implicitly or explicitly, planning for construction involves selecting technologies. The classification system can assist in identifying operations for which the conditions present on a specific project result in high risks or an opportunity for improvement. This will allow planning efforts to focus on ways to decrease risks or take advantage of opportunities to use a superior technology. For example, if analysis of concrete transportation operations for a specific project indicated a high degree of influence by specifications, a high degree of influence by the site conditions, and a high degree of supervisory involvement, conventional technologies may not achieve the desired results.

The increasing technological competitiveness of construction markets brings about the need to find opportunities to gain competitive advantage based on technology and to forecast changes in needs and availability of advanced technology (Tatum 1986a, 1988). The technological classification of construction operations could provide a way to conduct this analysis. For example, managers in firms could use the classification to systematically assess the state of technology used by the firm and its competitors and identify advantages, deficiencies, and opportunities to gain further competitive advantage.

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