Core Elements of Construction Engineering Knowledge for Project and Career Success

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Abstract: Design and construction markets are increasing requirements for the constructed product and how the project team delivers it. These market demands for improved infrastructure and a more sustainable built environment are increasing the importance and scope of construction engineering throughout the project development process. Concurrently, many construction degree programs face pressures to increase coverage of construction management topics, leaving less time for construction engineering. Construction research, especially related to modeling and integration, has produced new technologies and capabilities to assist with construction engineering activities. These drivers lead to the central question addressed in this paper: What are the essential core elements of construction engineering knowledge to foster successful projects and careers? The purpose of the paper is to identify these elements of knowledge and their implications, including background and support for many related topics discussed at the Construction Engineering Conference held at Virginia Tech in September 2010. After defining construction engineering on the basis of the main activities it includes, the paper identifies and describes four elements of knowledge that it requires: technical fundamentals, materials of construction, construction-applied resources, and field construction operations. The description for each type of knowledge includes examples of activities that require it. The paper also includes implications and recommendations for educators to increase coverage of construction engineering, for the industry to assist in advocating and offering relevant courses, and for researchers to further develop construction process models and other tools with potential benefits for construction engineering practice and education. **DOI:** 10.1061/(ASCE)CO.1943-7862.0000306.

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Introduction and Need

Trends or drivers in current construction markets, research, and education create a major need and potential for improved project performance. Needs for global infrastructure development and renovation to increase capacity and to mitigate the impacts of climate change may exceed the capacity of design and construction firms. Increasing priority for certain project objectives and criteria, such as life cycle performance of the facility, is expanding the technical scope of buildings and infrastructure. New technology, such as increased integration and modeling, offers significant potential to help increase project performance but also requires new technical capability in firms and on projects. These changes in products and processes require new capability but also offer the potential for competitive advantage. Despite these opportunities and needs, other drivers are increasing emphasis of construction management topics in many graduate and undergraduate construction programs. This leaves little room in the curriculum for construction engineering.

David Johnston and other members of the Construction Engineering Education Committee of ASCE's Construction Institute have effectively advocated accreditation of construction engineering programs and professional engineering licensure for the construction engineer (Johnston 2007). Construction engineering relates strongly to several of the 11 criteria for accreditation of engineering programs: apply mathematics, science, and engineering; conduct experiments and analyze data; design systems within realistic constraints; function on multidisciplinary teams; identify, formulate, and solve engineering problems; communicate effectively; understand the broader impact of engineering solutions; engage in lifelong learning; and use modern engineering tools. The specific criteria for construction engineering programs highlight construction engineering and process design [ASCE's Body of Knowledge expands this list to 24 outcomes, 11 of which are classified as technical (Body of Knowledge Committee of the Committee on Academic Prerequisites for Professional Practice 2008)]. This classification of outcomes includes levels of achievement based on Bloom's Taxonomy of Educational Objectives, ranging from knowledge through evaluation (Body of Knowledge Committee of the Committee on Academic Prerequisites for Professional Practice 2008).

The purpose of this paper is to identify the key elements of construction engineering knowledge and propose actions to increase the availability and use of this knowledge to assist realizing the opportunities and overcoming the challenges created by the drivers previously identified. The main elements of construction engineering described in the paper include technical fundamentals, materials of construction, construction-applied resources, and field construction operations. The major sections of the paper identify and describe these elements and highlight implications and applications for stakeholders in education, research, and project delivery. Students can further develop and apply the knowledge elements for career benefits. This especially includes focusing on the elements with the greatest potential to add project value and gain early career benefits and focusing on the best ways to learn about these elements. Industry professionals can offer or assist with

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construction engineering courses that combine the key elements with examples from their own experience. Researchers can increase understanding and operationalization of the knowledge elements as a part of developing construction process models and other planning tools that can benefit both construction practice and education.

Construction Engineering Activities and Educational Goals

For this paper, we will define construction engineering as a series of technical activities throughout the project that assist in meeting all project goals (Tatum 2005). These activities include three types: design, resource-related, and integration. *Design* activities focus on temporary works and the construction plant (or production environment), along with planning construction processes (means and methods). *Resource-related* activities provide technical information, permanent materials and equipment, and construction-applied resources. *Integration* activities include representing construction in integrated project delivery and integrated work processes, especially early decision making, interpreting the plans and specifications, and transferring experience to other projects.

Construction engineering activities foster more productive, safer, higher quality, and more sustainable construction by providing the many types of resources needed to efficiently complete construction operations with minimum rework. These activities also increase the level of design-construction integration on a project and the potential for innovation in design and construction. This builds effective teams.

Defining the project approach and plan for construction engineering activities should include identifying critical construction operations, selecting the necessary construction engineering activities for these operations, and setting the schedule for getting the required people involved. The level of technical challenge of the project guides these choices. This includes site conditions, design complexity, risks of specific construction operations, cost and schedule demands, and other special conditions or requirements. The timing of construction engineering activities is significant. If the construction firm is involved early, then integration of planning and other technical support activities previously described can add substantial value to the project.

Core Knowledge Elements for Construction Engineering

A broad view of construction technology provides a comprehensive summary of construction engineering knowledge. Construction technology is the combination of resources, processes, and conditions used to produce a constructed product (Tatum 1988). Construction technology is closely related to construction methods that are the resources (nouns) and sequences of operations (verbs) required to build a portion of the facility in accordance with the project objectives.

This section describes four key elements of construction engineering knowledge: technical fundamentals, materials of construction, construction-applied resources, and field operations. See Fig. 1 for the relationships between these elements and the flow to apply them. These elements and descriptions are all positioned at a fundamental level to allow application for multiple types of construction. The following criteria govern the selection of topics to include in each of the core elements: (1) increase understanding of construction resources and field operations and learn faster and more in-depth from field experience; (2) apply to complete construction engineering activities, including design, resource supply, and integration; (3) increase communication related to construction engineering problems and solutions; and (4) support lifelong learning of empirical and fundamental topics.

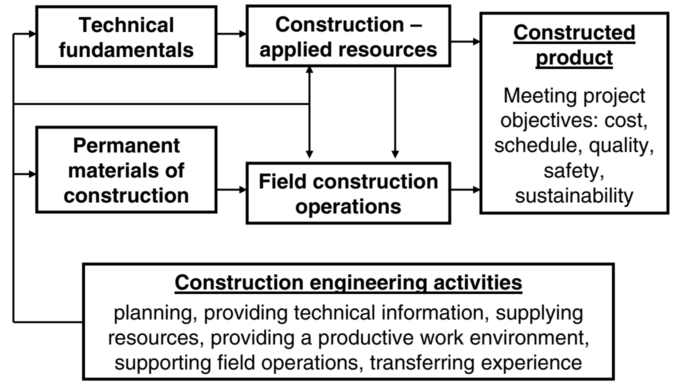

Fig. 1. Construction engineering activities and applications of knowledge elements

In addition to identifying the elements, selecting the appropriate level for different organizations is a major challenge. This can range from a qualitative survey of options for resources and operations to detailed technical design. The qualitative approach is more appropriate for engineers who work for program, project, or construction management firms or general contractors who do not self-perform any of the work. The technical approach fits engineers who work for general contractors who self-perform a substantial portion of their work or for specialty contractors.

Technical Fundamentals

Technical fundamentals provide a foundation or context to analyze and understand design and construction products and processes. They are the engineering basis for the performance of both the constructed facility and the resources and construction operations needed to build it. Understanding the technical fundamentals that apply to a specific construction resource or operation provides a basis to analyze, synthesize, and evaluate and a sense of limitations and relationships of the variables involved (Body of Knowledge Committee of the Committee on Academic Prerequisites for Professional Practice 2008). See Fig. 2 for an example related

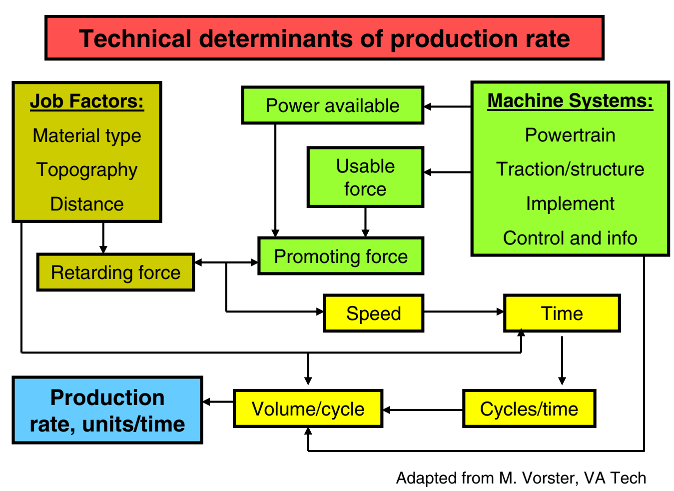

Fig. 2. Technical determinants of earthwork production rate

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to earthwork construction. Including fundamentals from multiple engineering disciplines as a main topic in construction engineering education recognizes the interdisciplinary nature of the field and provides a generalizable foundation for experiential and lifelong learning.

The major engineering disciplines involved in most types of constructed facilities include the following: materials science and engineering; mechanics and dynamics; geotechnical engineering; structural engineering; fluid mechanics; thermodynamics, psychometrics, and heat transfer; electric power; and process control and instrumentation. The scope of these and other disciplines applicable to a project varies by site conditions, type of facility, and phase of construction. Design engineers from each discipline apply engineering fundamentals to define the function and performance of permanent systems and to analyze and design the systems that make up the facility.

Construction engineers need to understand the engineering fundamentals used in each discipline, how they are applied in analysis and design of the permanent facility and temporary works, and what are reasonable results. This includes the design intent, the functions of each type system, and how they work (whether the system carries load down to a foundation or pumps water out of an excavation).

Knowledge of engineering fundamentals provides a basis for key construction engineering activities, especially providing construction input to design, interpreting the plans and specifications, and avoiding and solving field problems. This knowledge often allows the construction engineer to gain a qualitative sense of system design sufficient for many construction engineering activities. Greater depth, often involving quantitative application of the engineering fundamentals, is needed for more specific activities, including solving field problems. Construction engineers may develop this depth as required by job responsibilities or engage consultants with special knowledge and background. Both approaches require a basic level of understanding of the applicable technical fundamentals.

Specific examples of construction engineering activities related to technical fundamentals illustrate their application: (1) identify and explain how soil's properties change field construction operations; (2) describe the sources and paths of loads in a concrete form; (3) calculate the required head and horsepower for a specific application of a dewatering pump; and (4) give hydraulic analogies for voltage, current, and resistance in a feeder circuit for construction power. These types of activities indicate a need for a level of understanding of fundamentals that approximates that required for the fundamentals of engineering examination as a part of professional registration. Increased understanding of the fundamentals in preparation for the examination is another advantage of including them in construction engineering education.

Potential problems related to project objectives further illustrate the importance of understanding technical fundamentals. Examples of potential cost and schedule problems that require a basic technical background to anticipate and avoid include lower than expected production rates because of improper equipment selection. Potential safety problems include failure of temporary structures, large energy release from pressurized fluids during testing, loss of life from suffocation in closed environments, and electrocution. Potential quality problems that rely on understanding of technical fundamentals to anticipate and avoid include rework because of inadequate concrete curing or incorrect welding processes and excessive deflection of formwork and resulting noncompliance with location tolerances. Related to sustainability objectives, noncompliance with regulatory requirements can result from limited understanding of processes of soil erosion or air pollutant emissions from construction equipment.

Materials of Construction

The basic bulk materials of construction are soil, concrete, steel, other metals, and architectural materials. Engineered materials include permanent equipment and fabricated portions of distribution trees in systems. The content for construction engineering education related to materials of construction includes design properties and construction properties. Design properties include chemical, physical, performance requirements and special restrictions, such as toxicity. Construction properties of materials include cost, availability, potential for substitution, interdependency with construction operations, potential for change during field operations, toxicity, and others.

Knowledge of the basic materials' properties and of the standards that define them, such as those developed by ASTM, is necessary to understand design intent and avoid and solve field problems. Design and construction properties of materials are often a key consideration in establishing many types of design requirements and in evaluating alternate construction methods.

Design and construction properties of materials are a major part of the shared knowledge required for effective design-construction integration. Materials of construction and field operations are highly reciprocally related; they influence and constrain one another. This means that selecting materials of construction requires knowledge of field operations and that planning construction operations requires knowledge of materials properties. Potential problems from lack of technical background regarding materials include use of the wrong temporary or permanent materials. This can create problems related to each type of project objective.

Several types of construction engineering activities relate to materials of construction, including the following: (1) explain the implications of cement hydration for concrete construction operations; (2) identify and evaluate properties of steel that influence weldability; (3) identify examples of design criteria for process piping systems and the materials required to satisfy these criteria; and (4) review conduit configuration for possible restrictions on cable pulling.

Construction-Applied Resources

To build the work, construction forces use many types of materials and equipment that do not remain with the completed facility. These construction-applied resources include consumable materials, salvageable materials, tools of many types and sizes, and construction equipment, primarily for lifting and earthmoving. Several criteria guide the selection of construction-applied resources to include in construction engineering courses. These resources should be widely used on different types of projects. Use of the resources should significantly affect meeting project objectives. Young engineers should be involved in the selection and use of these resources. If applicable, the resources should include an application of information technology. The capabilities and limitations of construction-applied resources are often the major consideration in selecting construction methods. Examples include lifting capacity for construction cranes, production rates for earthmoving equipment, capability and flexibility of welding equipment, and strength and durability of plywood sheathing for formwork.

Important construction engineering knowledge related to resources includes technical requirements and performance for typical uses, how it works, capabilities and limitations, best applications, degree of mechanization and potential for automation, major risks of use, implications for all types of project objectives, and examples of evaluation and selection. For more complex and

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critical construction resources, such as large cranes and construction equipment, full understanding of capabilities and applications will require analysis at a systems level, such as traction or power train for earthmoving equipment (Tatum et al. 2006).

Construction engineering activities related to construction-applied resources illustrate their application. Examples include the following: (1) contrast the capabilities and performance of an excavator and a wheel loader for digging an underground parking structure; (2) prepare an erection plan for a two-tier steel building, including equipment selection, location, erection sequence, and rationale; and (3) list the contents of a well-equipped trailer for crews that pull electrical cable.

Potential problems related to project objectives illustrate the importance of understanding construction-applied resources. The major type of potential cost and schedule problem that requires a basic technical background to anticipate and avoid is selecting equipment that will not meet planned production rates. Potential safety problems relate to the capacity of each type of resource or the potential toxicity. Avoiding potential quality problems requires knowledge to select resources that can comply with criteria, such as welding equipment and processes to satisfy nondestructive examination. Examples of resource risk related to sustainability problems include use of toxic materials or equipment that produces noise in excess of allowable values for the project site.

Field Construction Operations

Completing any part of a constructed facility requires a series of field operations. At the most basic level, these include cutting, shaping, preparing, positioning, placing, connecting, coating, testing, and other special operations. These activities required to complete a specific type of work follow a typical sequence:

- *Earthwork*: erosion control; clear and grub; strip topsoil; excavate, haul, place, compact, and test soil materials; finish grade; and check surfaces.
- *Concrete*: fabricate and erect formwork; place reinforcing steel and other embedded items; batch, transport, place, finish, cure, test, and repair concrete. Concrete work may also include special methods and operations such as precasting, shotcrete, underwater concrete, slurry wall construction, and roller compacted concrete.
- *Structural steel*: order and detail steel shapes; fabricate, coat, transport, and shake out fabricated steel members; complete preassembly of large members; raise and connect steel members; place decking; plumb the building structure; and test connections.
- *Permanent equipment* for building or plant systems: specify performance requirements; review technical information from suppliers; fabricate and test equipment; transport, receive, and store equipment items; and install, connect, and test completed equipment.
- *Piping and ductwork*: detail, coordinate, and fabricate pipe spools or duct pieces; and transport, erect, support, connect, and test pipe or duct branches.
- *Electrical systems*: detail, coordinate, fabricate, transport, and install raceway; and transport, position, pull, terminate, and test electrical cable.

Priority learning for each type of operation is determined by the knowledge required to complete the required construction engineering activities. It builds on prior coverage of technical fundamentals that govern and the materials and other resources required. Key knowledge of construction operations includes design requirements, acceptance criteria, potential for improvement, risk of not meeting specific project objectives, methods to forecast production rates, and examples of analysis and selection.

Examples of construction engineering activities related to field operations include the following: (1) forecast expected production rates (yd^3/h) for a specified compaction operation; (2) identify key design and site factors to select the method for a specific concrete placement; (3) forecast the pieces of structural steel erected per day for a given condition of the site and the structure and the erection plan; (4) identify the characteristics of an HVAC dry system that influence erection sequence and coordinate with other trades working in a given area; and (5) contrast electrical cable-pulling operations through a cable tray raceway and through an electrical conduit.

Potential problems related to project objectives illustrate the importance of understanding the technical elements of field operations. Examples of potential cost and schedule problems that require a basic technical background to anticipate and avoid include selecting a method and operation that do not fit the site conditions. Potential safety problems include selecting work sequences that create unsafe conditions, such as working overhead. Potential quality problems can stem from selecting an operation that will not meet the acceptance criteria, such as shotcrete when surface finish is critical. Related to sustainability objectives, problems can result from selecting operations that do not comply with permit restrictions.

Conclusions, Implications, and Recommendations

The analysis of construction engineering knowledge in this paper leads to conclusions regarding the critical need for this background and a helpful structure for its key elements. These conclusions highlight implications for all the stakeholders in construction engineering activities.

Need and Elements

Need

Challenging projects, new requirements for field operations, new materials, and new IT-enabled resources for construction increase the need for attention to construction engineering. The combination of opportunity in specific market segments, new uses of information technology, and the interests of young engineers prompt opportunities for many types of rewarding career paths related to the built environment. Knowledge of construction engineering fosters increased success in all of these paths. Despite this, many factors have increased the focus on construction management topics and decreased coverage of construction engineering in many parts of construction education.

Construction engineering activities are critical for project success in meeting all types of objectives. Completing many of these activities early in the project increases the alternatives available for design, construction, and the value chain, along with the potential for integration and innovation. Without this, construction crafts complete the activities required for the construction operations they perform in the field, making the best they can of the constraints they inherit.

Construction engineering knowledge, carefully applied and diligently pursued, will provide a major career advantage. It will help individuals ask the right questions, better understand the answers, and synthesize the knowledge gained. It will foster critical analytical thinking to increase performance and continue learning. A foundational understanding of the four elements will help construction engineers select and excel in a chosen activity, bringing increased visibility and responsibility. The challenges and risks of construction operations highlight the need for a fundamental technical understanding up through operations and even senior

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management. Experience with construction engineering activities is a very good way to gain this knowledge.

The structure for construction engineering knowledge developed in this paper can help highlight career benefits from this background and career paths that apply and enhance it. It will also assist in abandoning traditional discipline perspectives to consider all types of fundamentals and materials that relate to construction resources and operations. The knowledge about resources can hopefully rekindle youth's excitement about construction, as illustrated by the popularity of *Bob the Builder*.

The knowledge about field operations will hopefully create a motivating preview of the satisfaction that comes from contributing to the built environment. It also provides a way for contributions to increased sustainability, a growing interest for many students and graduates. Finally, related to restoring the balance between construction engineering and construction management, an increased scope of construction engineering education can strengthen the construction management portion of programs by providing technical understanding and content for effective use of management techniques and tools.

Elements

The structure of construction engineering knowledge described in this paper includes two fundamental and two applied elements. All are important, but their relative emphasis can vary on the basis of the goals of specific courses or the requirements of specific projects. The elements present a challenge in selecting depth and breadth.

Technical fundamentals are an essential basis for gaining other types of construction engineering knowledge and for the evaluation of alternatives for construction methods. Material's properties determine the performance of temporary and permanent facilities and components. These two fundamental topics provide a basis for learning about resources and operations, the other two key elements of construction engineering knowledge.

Construction-applied resources, used to complete construction operations, transform permanent materials into a constructed facility. Coverage of construction operations captures how to build the work, including field challenges. The full scope of construction engineering includes other specialized topics, but these four can provide an effective foundation for continued learning throughout careers in design, construction, or other parts of the project life cycle and on different elements of the built environment.

Some background regarding construction engineering knowledge is highly beneficial, even if not comprehensive. The prominent place of fundamentals and materials in the elements recognizes the major importance of young engineers learning on the job and provides a foundation to increase the depth and rate of this learning. A separate description of the elements, although a necessary starting point, does not recognize their integration and interdependence.

Implications and Recommendations for Stakeholders

Increased effectiveness in meeting the challenges of providing the built environment creates a need for action by a large and diverse group of stakeholders. These include young engineers, industry professionals, and faculty.

Young Engineers

Many professions and craft-based organizations include requirements for continuing education to support continued personal development, introduce specialized topics to fit career paths, and keep current with the field. New applications of information technology, new design requirements, and new technical features of resources for construction operations illustrate the many types of beneficial topics for continuing education in engineering and construction.

One beneficial approach for continued learning during design and construction careers involves alternating between two types of construction engineering knowledge and learning methods. The first step is experience-based or empirical learning regarding design and construction practice related to materials, resources, and operations. The second step is self-study to gain deeper understanding of the technical fundamentals that are most applicable to the empirical knowledge gained in the first step. Developing professionals can then use the new fundamental knowledge to gain and further analyze new empirical knowledge. The Internet provides an increasingly valuable resource for this second step. An iterative process between fundamental and empirical knowledge provides a deeper and broader basis for continued learning from experience.

Regular and Adjunct Construction Faculty

Considering the elements of construction engineering knowledge identified in this paper will hopefully encourage increased coverage in undergraduate and graduate construction programs. This should include analyzing linkages with construction management topics in the program to leverage both parts. Developing a shared approach that includes the fundamentals along with examples described by an industry professional can increase both learning and interaction with the industry.

A core of basic teaching materials for each of the elements would help additional faculty offer construction engineering courses. The author is developing these materials, including notes and class presentations, to make available for the construction education community. They will allow selective use and tailoring to fit the objectives of courses offered by either regular or adjunct faculty. They will complement the many excellent textbooks available to describe some of the elements of construction engineering knowledge and help direct students to these sources for increased depth (for example, see Nunnally 2011; Peurifoy et al. 2011). The increased availability of textbook chapters from publishers will provide additional flexibility to fit the needs of many different types of construction engineering courses.

Industry Professionals

Many construction people want to give back to the industry. The special needs for construction engineering education provide an opportunity for them to make a real difference in improving the built environment. Professionals in many design and construction firms provide very valuable support for construction engineering education by participating in seminars or teaching courses, sharing information about their firms or projects, and advising students. The structure of construction engineering knowledge described in this paper can assist in focusing the industry activities on topics that will best meet the students' career needs. Construction firms can also gain benefits from this structure for internal training and knowledge management.

Construction engineering courses present special opportunities and challenges for involving industry professionals. After successful careers with increasing levels of responsibility, professionals from design or construction firms may tend to emphasize management topics rather than the technical input that best supports construction engineering learning. Younger engineers who are currently involved in construction engineering with general or specialty contractors or more experienced engineers who followed a technical career path are likely to have more success in this role. Especially beneficial activities include preparing course modules and class exercises on the basis of their own experience and

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advising student groups regarding specific problem- or project-based assignments.

Construction Researchers

Many construction researchers are now focused on developing model-based tools to assist in analyzing design alternatives and selecting construction methods that best meet all project objectives. These new tools can provide major benefits for construction engineering education by helping to bring the jobsite into the classroom. The elements of construction engineering knowledge can assist in structuring internships to collect data for research. This experience can greatly assist in defining problems and questions before developing solutions and in validating research results after they are developed.

The four types of construction engineering knowledge identified in this paper can also provide assistance in selecting the scope of representation and reasoning for the models. This can assist in tailoring the models to the owner's priorities for project objectives, the type of construction (buildings, plants, infrastructure), and the special challenges of the site.

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