

Rethinking Construction Education: Lessons Learned from Industry Innovations

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Over 25 years ago, the construction industry recognized the need to improve value in design and construction. Many contemporary innovations enable the construction professional to actively contribute to value creation and problem solving during the design process. While these opportunities represent a paradigmatic shift in construction practice, the challenge to develop the corollary skills is not always reflected in construction education. This paper describes three perspectives of change to the value creation process through narratives from construction practice: 1) revisiting assumptions of decision hierarchy and phase sequencing resulting from net-zero energy goals, 2) developing continuing improvement skills for collaborative problem definition and solution design, and 3) gaining knowledge beyond the mastery of tools and skills. These practice-based examples are examined from the perspective of normative construction education, and subsequent opportunities for instructional and pedagogic change are considered. These changes are in the realm of interdisciplinary thinking, design thinking, and critical thinking.

Key Words: construction education, innovation, value, industry, interdisciplinary

Introduction

For more than two decades, innovations in design and construction have occurred at a tremendous pace. The initial changes were triggered by research identifying low productivity in the construction industry and the need for increased innovation and constructability input in the design phase (CICE, 1983; Tatum, 1987; Tatum, 1989). The ensuing 25 years have been marked by experimentation with the sequencing of project design and delivery phases, enhanced partnering agreements, and increased collaboration between stakeholders. The AIA facilitated the change to the design hierarchy with the introduction of Integrated Project Delivery contractual documents. Lessons learned from lean manufacturing provided inspiration not only for efficiency improvements in construction production, but also the opportunity for continuing improvement to product value through early contractor involvement (Oglesby, et al., 1989). This shift to a focus on value management is supported by research in construction on improved identification of client value in the design phase and the management of this value in production (Male, et al., 2007).

Collectively, these innovations represent the development of concepts, methods, and applications of what can be called *value creation*. Each of these innovations facilitates the integration of construction processes with design processes. With all of these changes, the opportunity for the construction professional to contribute to value creation in the design process represents a paradigmatic shift in construction practice. What does this shift toward design innovation mean for construction education? How might contemporary industry practices suggest changes to classroom content and curricula? While the scope of today's industry developments cannot be completely analyzed in a brief study, three examples of contractor innovations will be presented here. Each one will serve as the basis for consideration of current normative practices in construction education and suggest opportunities for changes in instructional content and pedagogy.

1. Net Zero Goals Challenge Current Assumptions

Among the most far-reaching challenges to contemporary AEC practice is sustainable design, construction, and operation. In a classic design process, the architectural geometry is established as the first phase of the design and construction process and often drives the economic equation. All other decisions related to structure, mechanical systems, and constructability are typically subordinated to design and are addressed sequentially in the design process. In normative practice, constructors follow the design produced by the architects and engineers. The following example from industry suggests that high efficiency energy goals may challenge these basic assumptions of the stakeholder hierarchy and sequential workflow, and instead encourage knowledge of constructability at much earlier stages in the collaborative process.

Net-Zero Energy Goals Driving Design: Practice

Increasing awareness of sustainability issues facing the building industry has raised the benchmarks for energy efficiency with the ultimate target of a zero carbon footprint set by popular initiatives such as Architecture 2030 (2010). However, current green building practices have only resulted in average energy savings levels of 13.6% according to McGraw-Hill Construction (2011). Much of this has been through enhancement of current technology: increased insulation, improved air-tightening, or more efficient mechanical equipment. In order to achieve the target of net-zero energy consumption, design strategies will need to exceed “bolt-on” measures and adopt a whole systems approach. It will also require a more active involvement of technical expertise in energy modeling, building science, mechanical engineering, and renewable energy technology. Much of the energy modeling software has been developed as extensions to building information modeling (BIM) software and has typically resided in the domain of the architect. However, the increasing levels of complexity and performance expectations may call for increased collaboration between mechanical engineering skills and the design function. In such a scenario, the input of the mechanical engineer will be required earlier in the conceptual phase of design. The design itself could become driven not by aesthetics but by opportunities for energy efficiency, such as solar gain or wind capture.

An example of this kind of value creation can be found in the work of Affiliated Engineering, an innovative mechanical engineering firm in central Wisconsin. The firm has proposed an innovative goal of designing buildings for total passive heating/cooling and 100% daylighting, only adding supplementary mechanical HVAC equipment and artificial lighting as needed. This is a radical mental shift from the traditional reliance on mechanical equipment and has a clear and direct impact on the design process. With high expectations of building performance, constructability issues become increasingly salient as the thermal dynamics of the building envelope may be presented as performance criteria rather than as prescriptive specifications. This creates an opportunity for a contracting company to contribute to the building design by developing proficiencies in design and installation of high performance building technologies. Indeed, the expectations of building performance place a greater emphasis on the quality of the installation. This quality can be measured at the point of the individual trades as well as the interface of the trades because it impacts the overall detailing of the thermal envelope.

While this net-zero design approach currently represents the cutting edge of the industry, it provides an indication of the shifting stakeholder roles and sheds light on the expectations that students may experience in future practice. One of the significant learning opportunities in this example is to recognize the ability of the net-zero energy goal to transcend the fragmentation of the industry and thus create a dialogue among the trades.

Net-Zero Energy: Existing Education and Opportunities for Change

How would current construction education prepare students for this challenge in net-zero energy? A key instructional component to this form of value creation can be advanced through the development of *interdisciplinary thinking,* where work with construction content is integrated across AEC disciplines. Most of the general knowledge about mechanical systems and their performance characteristics are developed by construction students in dedicated MEP lecture courses. Though some advanced construction programs include specific coursework in environmental science, most MEP classes include those foundational scientific concepts—climate, solar heating, thermal resistance, and energy transfer—upon which the design of mechanical systems depend. As the efficiency of mechanical systems has become central to improved building energy efficiency, energy modeling software as a component of BIM is increasingly being introduced in MEP courses as well as stand-alone sustainability courses. In a 2011 survey of AEC educational programs, the highest level of adoption of BIM and sustainability courses was identified within architecture, with lesser adoption levels in engineering and construction (Becerik-Gerber, et al., 2011). The survey also measured the percentage of these courses that specifically included energy modeling software in addition to design software. The data indicated an inclusion of energy modeling in 30-50% of the architecture programs, in 20-30% of the construction management programs, and in less than 10% of the engineering training. Thus, the current educational trend for energy modeling software continues to favor the architectural domain rather than construction or engineering education. However, it seems clear that the preconstruction skills of selecting and analyzing high-performance building components may represent a significant opportunity for future construction professionals. Having the skills to use and understand energy analysis software as it relates to schematic BIM models could be incorporated into coursework issues of constructability, jobsite management, monitor and control methodologies, as well as building commissioning and operations. Since the value creation in these activities all intersect with those of building design, the skills of interdisciplinary thinking must be learned in order to engage them.

Independent of BIM software, the contractor has additional opportunities to contribute to improved sustainability. The previous example identified an opportunity for the construction firm to “own” the building envelope and gain mastery in the constructability information and building science analysis of high performance building components. Contractors have an opportunity to work with the manufacturing industry to provide product feedback and develop efficient installation techniques. They can also participate in laboratory testing; for example, contractors could assess wall detailing for building science considerations. Contracting firms can also develop systems for jobsite waste management, commissioning, and supply chain management. Existing construction curricula generally do not include courses that address these opportunities, as they are seen to belong to other disciplines like civil engineering, building science, industrial design, and management science. In order to prepare for this type of interdisciplinary thinking, Tinker and Burt suggest that construction students must be educated with a whole-building mentality to realize the interrelatedness of building components “in lieu of the current method of teaching compartmentalized information applicable only to constructors” (2004, p. 29). Mead (2001) proposes that sustainability ideas can be integrated into existing construction courses such as Materials or Means and Methods. But these ideas for change will require pedagogical modifications to courses as well. Where the creation of new forms of value requires interdisciplinary thinking, classroom assignments should provide students with cross-disciplinary content engaged through synthetic problem solving that parallel those same skills in interdisciplinary practice. Improving student learning outcomes in something as complex as constructing a high-performance building façade will require modifications to typical lecture course delivery methods.

2. Continuous Improvement Skills

The complexity of AEC projects today demands a creative mindset. Shigeo Shingo, the engineering mastermind behind the Toyota production system, declared that most engineers were characterized by their limiting focus of developing only one right answer for a defined problem. Toyota chose to not hire this type of engineer, seeking out instead the “continuous improvement engineer,” who placed a greater emphasis on defining the right question through observing the problem, identifying the root cause, and then creating solution scenarios collaboratively with the workers and management (Shingo & Dillon, 1989). The following examples demonstrate the benefit of applying this same approach of continuous improvement to the construction industry.

Continuous Improvement for New Structures: Practice

Concrete is one of the oldest building materials, the earliest examples of which are still standing from the Roman Empire. After so many centuries, it might be assumed that no further innovations in concrete are possible, yet the boundaries of this material’s abilities continue to be tested. When architect Jeanne Gang designed the Aqua Building in Chicago, she envisioned an undulating exterior façade but wanted to avoid the awkward space challenges that a curving wall would create (Van Hampton, 2008). Gang worked closely with the structural engineer and the concrete superintendent to explore the possibilities of extreme cantilevers of up to 12 feet, doubling the more typically accepted limits of a concrete span. These professionals drew on the knowledge from the design of the nearby Marina City building—a Chicago landmark completed in 1964 that experimented with a tapered slab and larger-than-normal columns. They also created a new slab forming technique with a reusable flexible steel strip to mold the curvy exterior edges. The resulting wavy exterior façade simplified the constructability of the structural exterior walls, took advantage of the cantilevers for improved views of Lake Michigan, and captured the effect of solar shading from the balconies on the large glass exposure of the exterior walls. Gang is known for her willingness to collaborate and learn from the trades.

A second example also involves leveraging the spans of concrete floor slabs, albeit with different motivation and a different set of outcomes. The Banner Bank in Boise, Idaho was originally designed as a fairly standard office complex with a modest green building goal of becoming LEED certified. However, the introduction of an integrated design process and delivery method helped the team “break through the old construction and design paradigm” and “transform the team members into more effective owners, designers, and builders,” eventually resulting in a LEED Platinum building for less than the original budgeted cost (Hellmund, et al., 2008, p. 1). The open discussions and inclusion of trades in the design process provided the collaborative freedom to share ideas for building improvements. For example, the team discussed the possibility of creating a column free floor. Typical column spacing in an office complex is based on traditional wide flange beams, which account for the majority of layout inefficiencies and directly impact the owner’s value proposition. The structural engineer on this project drew from previous experience with castellated beams and proposed a design that could handle larger spans, use less steel, and reduce the quantity—and therefore the cost—of columns. The long-term impacts of this decision were considerable. Improved interior clear spans provided space flexibility for tenants while minimizing owner churn costs. The open plenum of the beams eliminated the need for smoke detectors, and the openings themselves were used to route piping and electrical runs, which meant the acoustical ceiling could be hung closer to the bottom of the beams. This, in turn, presented the opportunity to decrease floor-to-floor height, and the building was able to accommodate an additional floor of office space (Hellmund, et al., 2008). The team credits the process of collaborative design in face-to-face meetings with creating opportunities to reveal design efficiencies, but an equally important factor was the ability of the structural engineer to identify the parameters of the problem, leverage his knowledge, and contribute to the solution design.

Continuous Improvement: Existing Education and Opportunities for Change

How would current construction education prepare students for this kind of improvement engineering work in building structures? A key instructional outcome to value creation in structures can be engaged through the development of *design thinking*, where multivariate construction problems are solved through iteration and critique. Structural knowledge is central to the integrity and safety of all construction projects and, as such, has always been foundational to construction curricula. In normative structures courses, theories and behaviors of structural systems are taught linearly from basic concepts to more complex applications, which typically follow material typologies from wood to steel to concrete. Construction curricula have largely inherited this sequence of structures content from civil engineering where these courses arose and where they are still frequently taught. However, research points to an ongoing concern about engineering education in providing students with problem solving abilities and the mix of skills and experience that would provide the best balance between design and engineering science (Dym, 1999). Critics of the existing system point to the highly structured, locked-in serial course sequencing that typifies engineering curricula. While this reflects the much needed building-block approach to learning the skills and tools of engineering, the students’ ability to internalize this information may be limited by the seemingly disjointed and abstract nature of the courses. Dym (1999) argues that engineering is conveyed primarily in the language of mathematics and as a science in which the analysis is based on pre-defined problem sets, and yet it is the ability to *design* that is identified as the distinguishing mark of the engineering profession. In the examples of improvement engineering previously discussed, it is precisely this design ability that is the source of value creation: to see multiple scenario sets and work toward synthetic solutions.

ABET and the professional societies have begun to push for more design methodology and design practice to be introduced in the engineering curriculum. One of the more typical approaches has been the inclusion of a capstone course in the final year of the program. However, in a literature review of over 100 papers on capstone programs, Dutson, et al. (1997) caution that waiting until the senior year to introduce design skills is too late, and that simple design problems introduced in earlier years will help the students gain the expertise for the larger capstone challenge. While construction education has to develop structural knowledge and the understanding of engineering requirements for structural safety and durability, there is reason to encourage a broader understanding of structures as they relate to more synthetic design innovations where constructors act in collaboration with designers. Construction education should also learn from engineering education that design thinking is a skill that cannot wait until the last years of a curriculum to be developed. Where design thinking offers value creation in the innovation of building structures, design opportunities could become an essential part of construction structures courses in terms of performance-based criteria selection, constructability and prefabrication potentials, as well as new applications in assembly systems and robotics.

3. Value Management—Gaining Knowledge beyond Skills Mastery

The full scope of what a constructor knows about a project is becoming a significant source of value to an owner. In construction, there is a distinction to be made between gaining mastery of tools and skills and the extraction of knowledge from this work. Smith and Tardif describe the learning process as follows: "data analyzed becomes information from which conclusions can be drawn to gain knowledge, which leads to the insight we call wisdom" (2009, p. 173). They further note that, in the current state of the building industry, we know "desperately little about the connection between our actions and their consequences" (p. 173) and urge the industry to transform itself into a learning organization, which is a model of management philosophy pioneered by Peter Senge at MIT (1990). The following example describes a learning approach to estimating, in which the contractor leveraged the accumulated data to gain insight on the contribution to client value of proposed design alternatives.

Value Management through Estimating: Practice

Headquartered in Wisconsin, Boldt Construction has a long history of innovations in lean construction and integrated project delivery. They have been an active partner in the development of Target Value Design (TVD) for improved value management in the design process. One of the key characteristics of TVD is an iterative approach to design and costing, where design alternatives are proposed, evaluated, and selected in real time during the design process. Boldt's lead estimator recognized that traditional estimating approaches were limited in their ability to provide costing feedback that would correlate the costs of the alternatives with the targeted design values. To address this gap, he developed a cost estimating metric that compared the proposed project alternatives based on "program quality cost." This formula used the variables of: a) program elements, b) a building cost factor equalized for time and location, and c) a performance factor that related the equalized cost to an averaged baseline cost. As the resulting database becomes populated with data for both products and design alternatives, it provides an efficient process tool for identifying best value. While the contractor recognizes the considerable contribution of this tool to the feedback of design alternatives, he also proposes an additional opportunity for estimators to take a more proactive role in the design process. Estimators could leverage their accumulated data and knowledge management to serve as a resource in the collaborative design. While Tatum (1987) had proposed this facet of constructability in industry reports of the 1980s, such an approach still represents the current leading edge of industry innovations.

Value Management: Existing Education and Opportunities for Change

How would current construction education prepare students for this kind of value management work across a curriculum? The key instructional outcome to value creation in design and cost management can be brought to the classroom through the development of *critical thinking*, where the work of analysis and synthesis is brought to problem definition, facts and resources, solution alternatives, and judgment. Among the most significant characteristics of the TVD system as developed by Boldt was the iterative sequence of problem solution: framing, proposition, then evaluation and decision. This fundamentally reflective activity is premised on critical thinking skills developed through problem solving.

The weakness of undergraduate education to accomplish student learning outcomes in critical thinking is becoming more and more evident (Bok, 2006). Though there are no studies specifically regarding construction students, Bok suggests that this underdevelopment in critical thinking is a function of instructional pedagogies like the lecture course model that generally lack opportunities for students to do problem solving. This same effect was recognized by the 1986 Neal Report criticizing undergraduate STEM education in the United States, after which nearly all of the engineering and science disciplines have made shifts toward problem-based student learning to improve the student's ability to apply practical knowledge for disciplinary practice (Monson, 2011). This type of instructional change in construction education would represent a significant move toward building skills like TVD and value management across construction content areas. As an example of problem-based learning, Davis and Cline (2009) review a hands-on learning laboratory designed to augment the learning experience through "real-world" problems, and Fiori and Songer (2009) cite examples of the experiential learning that can be gained from service projects through journaling, peer-to-peer interaction, and faculty-led feedback sessions. However, a distinction should be made between skills mastery and the deeper level of knowledge gain. Monson (2011) reviews current problem-based coursework and suggests that the existing paradigm of the traditional course set-up reduces the scope of problems in order to become testable and measurable, thereby reducing the authenticity of the problem and the opportunity for inquiry and learning. He proposes the adoption of a studio environment that would support a discursive, collaborative, and cooperative learning environment. This innovative pedagogy has currently been adopted by Mississippi State University and California Polytechnic State University San Luis Obispo, and it shifts the relationship of teacher to student more to a role of master and apprentice (Monson & Hauck, 2012). Both Dym (1999) and Monson (2011) point to an obstacle in the implementation of this approach, which is the availability of faculty with the level of industry knowledge, skills in developing inquiry-based learning, as well as the requisite design thinking skills.

Discussion

In the examples discussed here of contemporary innovations in the AEC industry, there are many opportunities for change in construction curricula and pedagogies that would better prepare students for the forms of value creation essential to twenty-first century construction practice. These changes can be reflective of innovations developed in practice, and it is to the benefit of students and construction education in general that educators continue to monitor industry for new modes of professional practice that can inspire new models for construction education.

This study briefly engaged industry examples in sustainability, continuous improvement engineering, and value management in order to explore the potential opportunities to change construction education in terms of interdisciplinary thinking, design thinking, and critical thinking. While each of these three thinking skills would ultimately serve best as a pedagogical foundation of all coursework, the transition in construction education suggested by these lessons from practice will likely mirror the process of value creation experienced in industry: experimentation with *sequencing*, *partnering and collaboration*, and *invention*.

In terms of interdisciplinary thinking, a key mental shift with the adoption of high benchmarks of sustainability is the breaking down of traditional silo boundaries of the construction trades in order to address the systemic nature of sustainability. In construction coursework, this is a challenge of *sequencing*: remaking the traditional order of architectural design first and building performance and constructability issues afterward. Within existing curricula, many construction programs have Introduction to Construction and BIM/CAD courses where this kind of integration of design and construction issues can enhance the skills of value creation in sustainability. In introductory construction courses, students can learn about the broad array of AEC disciplinary players just as effectively through narratives of their collaborative value creation seen in high-quality sustainable projects as through the traditional design-bid-build delivery typical of introductory textbooks. The same thing could happen in BIM/CAD coursework. Beginning the construction of a Revit model from the perspective of the performance of the MEP system rather than the limits of a proscribed architectural envelope still teaches the necessary software skills. While this resequencing of design and performance is not meant to imply that construction students need to gain mastery over all of the topics of sustainability, it does highlight the importance of understanding the areas of overlap. It also presents the opportunity for constructors to take ownership of some of the components of the energy equation, such as the thermal envelope. This would suggest a more prominent role of building science in the construction curriculum and an increased emphasis on learning the energy modeling components of BIM software. Integrating these concepts into the learning environment could help students gain mastery over sustainability concepts, experience some of the obstacles in implementing these goals, and learn to identify the roles of other stakeholders in developing solutions.

In terms of design thinking, introducing authentic ambiguous problems as applied exercises within existing course topics can help students gain deeper domain knowledge and learn the analytical skills needed to frame problems. In construction coursework, this is a challenge of *partnering and collaboration*: rethinking the integration of design and construction through the development of the problem-solving skills required of interdisciplinary work. Within a construction curriculum year level, one such approach would be an ambiguous problem simultaneously assigned across several existing courses. For example, the problem might address contractor contributions to achieving net-zero energy goals. Replicating a process of integrated project design, students would meet in a facilitated workshop or studio environment over several weeks at their regular class meeting time. Students could do energy modeling as a part of an IT course, develop properties of wall materials as a thermal assembly for a Materials course, and sequence the detailing of the wall assembly in a Construction Principles course. Linking courses with common assignments leverages the existing faculty and curriculum infrastructure while introducing an opportunity for the students to gain deeper domain knowledge, learn analytical skills needed to frame problems, and build design thinking skills to develop potential solutions. Such an approach requires the active participation of faculty to provide guidance in problem solving strategies and also presents opportunities for industry mentorship and involvement in proposing work scenarios as problems for students. The scope of the problems can be successively increased, preparing the students for a more complex design problem in the capstone course.

In terms of critical thinking, there is an opportunity to develop students' abilities to analyze the subject content, the mastery of technical skills, and the application of these skills from the perspective of real world problems. In construction curricula, this is a challenge of *invention*: rebuilding instructional methods and pedagogical models to best meet the evolving knowledge and skill base required of twenty-first century construction professionals. Because this invention depends on significant modifications to course delivery methods, this is the most difficult type of curricular change to consider. Many construction management programs have faculty who use inquiry- and problem-based instructional methods in specific courses for specific assignments. Some faculty have changed entire courses to be based on student problem solving rather than lectures. There are also many examples of integrated construction and design coursework where the premise of the student effort is based on problem-solving. Much of this coursework in construction has been encouraged by the experiences from the related AEC fields of engineering and architecture, both of which have undergone considerable review and can help inform new ideas in construction—especially in the realms of problem- and inquiry-based learning. As previously discussed, a small number of construction management programs in the United States have modified or created curricula entirely based around six-credit problem-solving studios or labs, which is an instructional model taken directly from the design fields of architecture, landscape architecture, urban planning, and interior design. Whatever form of classroom context problem solving takes, students learn to problem solve by questioning the validity of the problem, the suitability of the tools, and the contribution to meaningful solutions. Smith and Tardiff (2009) propose that this emphasis on inquiry can facilitate the gaining of insight to lead to an increase in wisdom, which is the ultimate outcome of critical thinking skills.

To accomplish these thinking outcomes in construction education, there is the need for construction faculty to engage real-world professional practice so that the many innovations being developed can affect today's courses and curricula. This engagement creates new modes of practice-based research that can be combined with curriculum development, while it also builds professionals into potential classroom resources. As funding organizations become increasingly aware of the soft skills aspects of practice, there are opportunities for these seemingly disparate paradigms to be combined into substantive lines of research. Construction education programs are also leveraging the considerable experience of industry practitioners and incorporating their knowledge through adjunct faculty positions or other collaborative teaching arrangements.

If the question "Do you expect construction practice to look the same in ten years as it does today?" is asked, almost invariably the answer is no. This should be an important challenge to construction education. Given that the pervasive changes in the discipline have arisen largely from value creation innovations in the field, perhaps the same spirit of change that was launched in industry over 25 years ago can be applied to the rethinking of construction education today.

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