CEM Research for the Next 50 Years: Maximizing Economic, Environmental, and Societal Value of the Built Environment[1]

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Abstract: Construction engineering and management (CEM) research over the past 50 years has focused on extending and applying management and computer science approaches to minimize cost during the implementation phase of construction projects. Three emerging trends suggest the need to broaden the frame of future CEM research in several ways: (1) more integrated delivery of design, planning, construction, and operation of buildings and infrastructure requires us to broaden the focus of construction engineering and management research across the entire facility lifecycle; (2) rapid globalization of the construction industry requires new governance structures for projects that can bridge across the gaps in values, beliefs, norms, work practices, and laws between participants from different countries; and (3) heightened global awareness of, and demands for, enhanced sustainability requires new approaches, methods, and tools to incorporate sustainability issues in the early phases of the facility development process. Building on ASCE's 2006 Vision for the Future of Civil Engineering. This paper elaborates each of these three trends and draws implications for refocusing and redirecting construction engineering and management research, education, and civic leadership in the next 50 years.

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Construction Engineering and Management: Our Founders' Vision

Construction engineering and management (CEM) emerged as a field of graduate engineering education during the 1950s. Since then it has had 5 decades to mature as a respected field of graduate engineering education within civil engineering departments, and sometimes within architecture or building technology departments. It is useful to reflect on the vision for the field of CEM that the early founders of our field developed to shape the evolution of the discipline.

As a "second generation" CEM faculty member, I never had the pleasure of meeting Professor Robert Peurifoy. However I have had the pleasure to know, and interact with, all of the first eight Peurifoy Research Award winners:

- 1986 Richard Tucker;
- 1987 L. Richard Shaffer;
- 1988 Clarkson H. Oglesby;
- 1989 Ben. C. Gerwick, Jr.;
- 1990 John W. Fondahl;
- 1991 Robert B. Harris;
- 1992 Daniel W. Halpin; and
- 1993 Boyd C. Paulson.

Based on discussions with these academic pioneers in our field and others, it is clear that there were two elements to the vision that they shared for CEM as a graduate academic discipline.

1. First and foremost, they wanted to develop CEM into a legitimate "profession" comparable to other legitimate and respected "engineering professions." In the mid-1950s, there were virtually no graduate degrees in CEM, and professional registration was not available for "construction engineers." I have been told—but have no definitive evidence to support this—that civil engineering departments at a number of universities would channel their undergraduates whose cumulative grade-point average was below a "B" out of the traditional structures/geotechnical civil engineering track and into the construction management track.
2. Second, they wanted to develop a respected community of CEM researchers within their departments and schools. Engineering schools at a number of the nation's leading universities had placed a heavy emphasis after World War II on professional graduate education. United States universities in the late 1940s and early 1950s faced both a ready supply of students in the form of millions of returning GIs from World War II and the Korean War whom the labor market could not absorb immediately, plus a deep pockets sponsor—the GI Bill—to pay for their tuition. Professionally oriented MS degrees blossomed at this time at many United States universities. At the same time, many of the leading United States engineering universities were putting progressively more emphasis on fundamental research as the way to improve their standing in the academic community. Our pioneering faculty

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Note. As an honored recipient of the Society's Peurifoy Award, the author was invited to write this piece for the special issue celebrating the Journal's 50th anniversary. Discussion open until February 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript was submitted for publication on April 4, 2007; approved on May 2, 2007. It is part of the ***Journal of Construction Engineering and Management***, Vol. 133, No. 9, September 1, 2007. ©ASCE, ISSN 0733-9364/2007/9-619–628/$25.00.

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found themselves in the middle of this transition and developed a strategy to compete with other engineering disciplines as bona fide researchers. Of course, engineering is inherently an applied field, so fundamental research in CEM might still be viewed as applied research by natural scientists or social scientists. Nevertheless, the same could be said for other fields of engineering. So the early researchers in our field began to harness physics, chemistry, management science, and computer science (a discipline that had not yet been created, and to which civil engineers made seminal contributions in their development of databases) as the underlying sciences to help them analyze and optimize work processes and organizations for design and construction.

50 Years of CEM Research

The following section provides a review of the first 5 decades of pioneering research in construction engineering and management whose goal was to develop a research base for professional practice that would not be based entirely on field-level experiential learning. I ask the reader to appreciate that I have spent most of my professional career at Stanford University, so that my perspective on research in a field is obviously biased thereby. So, the researchers whose work is mentioned in this paper are intended to be illustrative rather than exhaustive; and since this paper is based on a lecture that lays out a big picture vision for the field rather than a detailed review of prior research, specific citations to the work of these researchers have not been provided.

First 2 Decades (1955–1975)

In the period from 1955 to 1975 several of the pioneering faculty in this field harnessed applied mathematics as their research tool. Professor John Fondahl at Stanford developed the "circle and connecting line diagram" which underpinned the precedence diagramming approach to the critical path method (CPM) for scheduling. This approach is being used today, largely unchanged, on construction sites around the world and for scheduling everything from dams, bridges, and buildings to marketing campaigns, software development projects, and moon shots.

Clark Oglesby and Hank Parker at Stanford and several faculty members at other universities began using and adapting techniques from industrial engineering to develop operations analysis and design approaches that could formalize, model, and optimize work practices on construction sites. Marvin Gates, Bob Carr, and others engaged in a decade-long intellectual debate about how best to model, simulate, and optimize bidding in construction using probability theory as their intellectual toolbox.

Civil engineers were leaders in the early days of harnessing computers to automate many kinds of engineering analysis. During the 1950s and 1960s, Steve Fenves, Lenny Lopez, Bob Logcher, and others helped to pioneer the Integrated Civil engineering Systems (ICES) family of computational analysis tools that successfully automated surveying calculations along with structural, geotechnical, groundwater flow, and other kinds of engineering analysis. One offshoot of this effort was computerization of CPM calculations. Researchers including Daniel Halpin and my late colleague, Boyd Paulson, began to develop stochastic simulation models using Monte Carlo simulation techniques to analyze and optimize the configuration of construction equipment fleets, and subsequently many other kinds of construction field operations.

Civil Engineering researchers of the 1960s invented the first general purpose database management systems for managing large data sets associated with engineering computations, and which were subsequently commercialized by companies like Cullinane, IBM, and, more recently, Oracle, to manage data for business applications. These database management systems (DBMS) made it possible to develop powerful commercial-grade software tools that helped to transfer the first tools for computer-based engineering analysis into engineering consulting practice.

By the early 1970s, several researchers were beginning to find ways to apply social science theories to help them understand and enhance many aspects of construction practice. John Borcherding's pioneering work on motivation of construction workers laid the groundwork for subsequent research on construction safety at Stanford and elsewhere by Clark Oglesby, Henry Parker, Nancy Samelson, Michal Robinson, Jimmie Hinze, the writer, and others that has had significant impacts on construction safety management practices worldwide.

Thus, an impartial observer could already see significant progress toward creating a research base for the CEM profession after just 2 decades of work by the pioneers of our field.

Second 2 Decades (1975–1995)

The period from the mid-1970s to the mid-1990s saw an explosion in the number of graduate CEM programs in the United States and around the world, and a significant growth in the breadth, depth, and quality of CEM research output. The *Journal of Construction Engineering and Management* of ASCE and the Construction Research Council of ASCE were well established by then, and played an important role in evaluating and disseminating this research. The National Science Foundation was routinely making grants in this field, with its rigorous external review process, and more applied research was being conducted by industry consortia such as the Business Roundtable, starting in the late 1970s, the Construction Industry Institute at the University of Texas, starting in the early 1980s, the Center for Integrated Facility Engineering at Stanford starting in 1988, and related NSF Engineering Research Centers at Lehigh and Carnegie Mellon Universities.

Researchers continued to find ways to apply mathematics and probability theory to problems of formal risk analysis. Professor David Ashley applied probability to analyze contractual risk sharing, and others continued to work in the area of bidding theory. The applied social science research in our field became more sophisticated, with CEM researchers making significant contributions to CEM practice and to social science theory. Examples include work by Julia Harkola and others on the roles of social networks in diffusing innovation; work by Bob Tatum, Sarah Slaughter, Hans Björnsson, and others on innovation and management of technology; work on "lean construction" by Greg Howell, Iris Tommelein, and Glenn Ballard; work on strategy in project based industries by Paul Chinowsky; and the writer's work in organizational design based on microcontingency theory.

Starting in the late 1980s, a group of researchers at Stanford University and California Polytechnic State University evolved a shared vision that the confluence of developments in computer-aided design tools, databases, and artificial intelligence were creating a significant opportunity for CEM researchers to prototype new kinds of intelligent, visual tools for planning and executing construction. After a joint proposal from these two universities to NSF for an Engineering Research Center was declined, a group of faculty at Stanford University launched the Center for Integrated

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Facility Engineering (CIFE) under the direction of Paul Teicholz as an industry-funded research center around this vision of exploiting computer-aided design (CAD) for visualization, artificial intelligence for automated reasoning, and database management systems for integration of data, to support multiple professional perspectives.

In the mid-1970s, computer scientists under the direction of Edward Feigenbaum at Stanford University developed a medical diagnosis program called MYCIN. MYCIN was arguably the first "expert system" in that it could empower novices in medicine to reproduce the reasoning processes of experienced medical professionals by chaining together production rules implemented as "natural language sentences" to propose diagnoses and request additional data. The underlying production rule chaining engine for MYCIN was immediately generalized by Bennett and Engelmore, and its second application was SACON, an expert system for configuring complex structural analysis problems. Subsequent expert systems like the PROSPECTOR system developed by Dr. Alan Campbell and his colleagues at SRI demonstrated that computers could also reason about two-dimensional (2D) and three-dimensional (3D) spatial structures to surpass the reasoning capabilities of human expert geologists and discover mineral deposits that human experts had overlooked. CEM researchers picked up both of these approaches in developing a wide variety of expert system prototypes, some of which evolved into commercial products.

Expert systems made rapid progress for use in many kinds of deductive tasks such as classification or selection for which there is generally a single or small number of correct solutions, but not in the much more open-ended problem space of design synthesis. In 1985, Mary Lou Meyer and Steven Fenves developed HI-RISE, the first application of expert systems that could perform structural design synthesis for high-rise buildings. Following their work, several CEM researchers began exploring uses of expert systems in construction including safety evaluation, design of hydropower penstocks, and automated building code interpretation. The first commercial spinoff of this work was when a company called Design Power in Cupertino, Calif. developed expert system applications to automate conceptual design of process plants, conceptual and detailed design of "pre-engineered metal buildings," configuration of uninterruptible power supplies, configuration of rack-mounted data center equipment, and a variety of other applications.

Expert systems were also deployed by Adnan Darwiche and the writer, and by Chema De La Garza and his colleagues at the University of Illinois, to automate the development of construction plans from CAD or other computer interpretable representations of a facility to be built. This approach to automated generation of construction plans was extended and integrated with visual planning techniques by Florian Aalami, and extended by Burcu Akinci to carry out automated work process interference checking and hazard analysis using spatial reasoning.

Starting in the 1980s several groups of researchers around the world began to use computers for automated pattern recognition, including multiple efforts to exploit the emerging technique of neural network analysis, and a smaller number of efforts to use various kinds of "evolutionary computing" approaches such as genetic algorithms and genetic programming to support optimization of design configurations for everything from earthmoving fleets to project organizations.

CEM researchers were now contributing heavily to publications like the ASCE *Journal of Computing in Civil Engineering* and some specialized new journals such as *Artificial Intelligence in Engineering Design, Analysis, and Manufacturing*.

As our field matured, CEM researchers were regularly collaborating with world-class computer scientists, social scientists, and management scientists, rather than trying to become "amateur" computer/construction researchers or computer/social science researchers themselves, as CEM researchers had mostly done during the first 2 decades. These kinds of collaborations with world-class scientists in the fundamental disciplines greatly enhanced the quality and stature of CEM research, and made CEM researchers more visible across multiple university departments starting about the mid-1980s.

5th Decade (1995–2005)

Perhaps the most significant impact on research in our field in the last 10 years has been the evolution of computers from "automated calculators" to "communication amplifiers." The emergence of Internet standards like TCP-IP for sharing data, and hardware that has increased the speed and reduced the cost of broadband communication to make it ubiquitous, has spawned research on collaborative engineering and collaborative project management. For an industry as fragmented as construction, this line of research offers extraordinary opportunities for enhancing the productivity, safety, and quality of our industry's products, processes, and organizations.

Many of our colleagues have begun to conduct research in this area during the last decade. For example, Professor Peña Mora at Illinois has been adding findings from social science, and Professor John Haymaker at Stanford has been adding ideas from cognitive science, to make these communications technologies even more effective in supporting collaborative design and construction of complex projects.

Semiconductor fabrication technologies, and more recently "nanotechnologies," have reduced the size—and even more dramatically, the cost—of sensors such as strain gauges, accelerometers, global positioning systems, and communication devices like radio frequency identification device (RFID) transceivers down to the point where they can be widely deployed in construction. CEM researchers are conducting research on innovative applications of individual sensors and sensor networks to support new kinds of automation and optimization of products and processes. The logical extrapolation of this trend is that buildings will become, in effect, giant robots that have considerable awareness of their current status, and the ability to reason about form, function, and behavior in ways that will make them truly automated building systems.

For example, Law and Kiremidjian at Stanford, and Wood and others at the University of Texas, Austin, are finding ways to embed low-cost, microsensor transceivers in building components so that they can be easily tracked during transportation and located in lay down areas during construction. Embedded in permanent structural elements like beams, columns, and slabs, these microsensor transceivers can provide detailed information about their loading, temperature, or related history. Moreover, they can report on their current status after high-stress events like a major hurricane or earthquake, allowing the building owner to assess the building's safety for reoccupancy and to pinpoint requirements for repair or replacement of building components.

The same kinds of microsensor receivers incorporating global positioning systems can be placed in construction equipment to make cranes more productive and safe, and to fully automate earthmoving equipment for some applications, e.g., the giant un-

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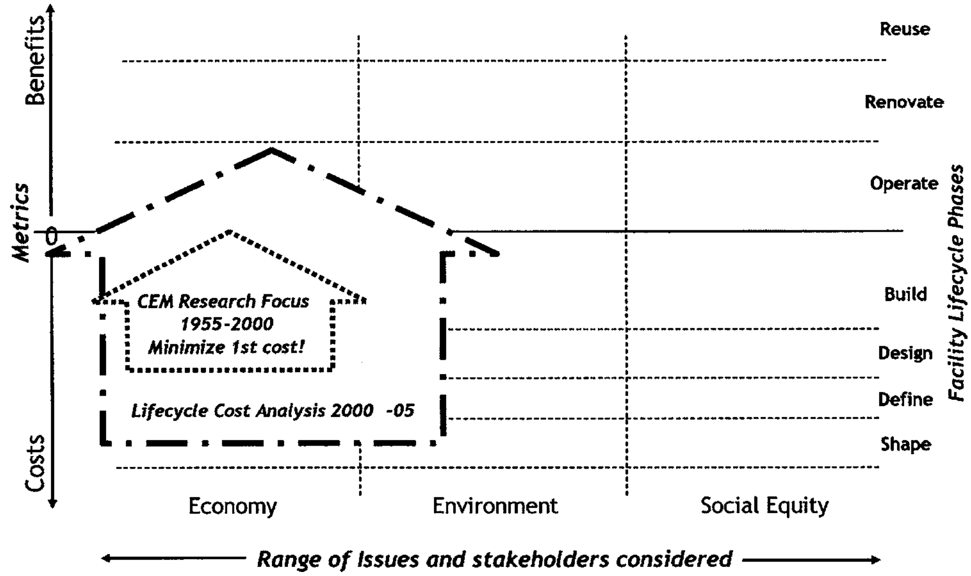

Fig. 1. Overview of first 50 years of CEM research

manned haul trucks one can currently observe being prototyped on test tracks for mining applications by organizations like Caterpillar.

The last decade has also witnessed new kinds of research on optimization and automation of work processes. Highly visual modeling of building systems, scheduled activities, and organizational responsibilities are being enabled by tools like Martin Fisher's 4D CAD research, the writer's work on modeling and visualizing information flow through project organizations, and the animated equipment fleets being modeled and visualized at Virginia Tech and the University of Illinois. These visual planning and management tools are moving us toward a totally new realm of planning construction projects—what my colleagues and I are calling "virtual design and construction (VDC)."

In our view, VDC is the integrated visual modeling and simulation of facility products, processes, and organizations. The fact that these representations are visual makes them accessible to a wide range of project stakeholders across language, cultural, and professional boundaries; and the fact that the models and simulations make predictions whose accuracy has been validated makes them extremely useful for exploring alternative approaches to the ultimate design of facilities, and of the processes and organizations deployed to create and maintain them. As the first generation of young professionals who grew up playing video games enters the profession, these tools will be readily assimilated and will become powerful ways for them to learn by "failing early and failing often" in the computer, to avoid failing late and expensively in the real world.

The combination of the VDC modeling capabilities and the collaboration technologies for sharing model results heralds a new and better way to plan, design, build, maintain, and recycle the buildings and infrastructure that are the basis of national wealth and the key to alleviating poverty in the developing world.

Finally, in the last few years we have seen research that begins to take more of a lifecycle perspective on costs and benefits of decisions made during design and construction. The input–output economic analyses of Chris Hendrickson at Carnegie Mellon University and Arpad Horvath at Berkeley, as well as multiple research groups in Europe, point the way to research that expands the metrics for judging the quality of construction beyond first cost in encouraging ways.

What Have We Achieved in the First 50 Years of CEM Research?

In this commentator's view, there is both good and bad news about what we have achieved in the first 50 years of CEM research.

Bad News about First 50 Years of CEM Research

First, the bad news: If one stands back from the research that CEM researchers have accomplished during this first 50 years of our academic field, what is most striking is that it has primarily focused on one phase in the lifecycle of facilities—the construction phase—without much consideration of what comes before or what comes after it in the lifecycle. This may not be too surprising, given that we have defined ourselves as "construction engineers and managers," but constructors do not operate in isolation in creating the built environment. Along with this focus on a single phase of the lifecycle has been a focus on the production cost efficiency of this part of the process, again in isolation, leading CEM researchers and the industry that we support to measure success almost exclusively in terms of reduction of first cost for facilities.

The result has been a set of valuable insights about how to build facilities that have lower capital cost, but which may perform very poorly in terms of lifecycle economic metrics—not to mention environmental or social equity metrics. Economic, environmental, and social equity metrics collectively provide a "3E" or "triple bottom line" set of sustainability metrics for assessing and optimizing the lifecycle value of the built environment. Given the unsustainable pressures that the built environment has imposed on the oceans, rivers, grasslands, forests, and atmosphere of our planet and the social disruptions and inequities caused by

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many kinds of construction, CEM researchers must begin to address these triple bottom line sustainability concerns urgently.

My conceptualization of the narrow sets of issues considered by, and the metrics for evaluating, CEM research in the first 50 years is shown in Fig. 1. The vertical axis in this figure shows the phases of the construction project lifecycle on the right, and highlights the corresponding point—the beginning of operations—at which the economic flows associated with facilities shift from costs to benefits on the left hand vertical axis. The horizontal axis looks at the range of issues of sustainability addressed by our research, with economic stakeholder issues on the left, environmental issues in the center, and social equity issues on the right. This figure highlights the fact that there has been an almost exclusive focus on economic stakeholders and economic aspects of sustainability during just the building phase of the overall construction project lifecycle to the exclusion of social equity and environmental issues and stakeholders.

Clearly, there is a huge agenda of research to be done to broaden the set of issues and stakeholders that our methods and tools must address in order to capture the lifecycle cost and benefit ("value") metrics of triple bottom line sustainability.

Good News about First 50 Years of CEM Research

There is also good news: It is my strongly held view that we have largely realized the vision of the pioneering CEM researchers and educators who founded our field of graduate study and research in the mid-1950s.

1. First, CEM is now viewed as a "real profession" by civil and environmental engineering (CEE) societies, ABET accreditation examiners, state engineering license boards, and our fellow practitioners. CEM practitioners and academics are regularly elected to leadership positions in ASCE; CEM now has its own section in the CEE professional engineer (PE) exam (with thanks to David Johnston and his team who created a section of the Professional Engineer's examination for CEM, and to Jeff Russell, who has been leading the push for a 5-year degree as the basis for professional certification in civil engineering).
2. Second, CEM research is now viewed as bona fide "engineering science" by engineering faculty and university administrators. Our colleagues are regularly being promoted and tenured at leading research universities and being appointed to the highest levels of university administration; and CEM has many first rate journals, conferences, and societies—and even prestigious research awards!

So, one might conclude that the founders' vision for the field of CEM has been essentially achieved, and is now "used up!" If the reader accepts this premise, then we need to ask ourselves, "What will be the vision that guides CEM research for the next 50 years?"

Let's begin by looking at the vision that the American Society of Civil Engineers has just developed for the field of civil engineering.

ASCE's Broad New Vision for Civil Engineering

In June of 2006, the ASCE Task Committee to plan a summit on the future of the civil engineering profession produced a report entitled "The Vision for Civil Engineering in 2025." The task force developed the following vision statement for the role of civil engineers in the profession and society by the year 2025:

> Entrusted by society to create a sustainable world and enhance the global quality of life, civil engineers serve competently, collaboratively, and ethically as master:

1. Planners, designers, constructors, and operators of the built environment, which is society's economic and social engine;
2. Stewards of the natural environment and its resources;
3. Innovators and integrators of ideas and technology across the public, private, and academic sectors;
4. Managers of risk and uncertainty caused by natural events, accidents, and other threats; and
5. Leaders in discussions and decisions shaping public environmental and infrastructure policy.

In the following section, I propose a personal vision for the future of CEM research that is consistent with this vision for the future role of civil engineers in a global society.

Personal Vision for Next 50 Years of CEM Research

My personal vision for the next few decades of research in CEM is as follows. CEM researchers should:

Ask and answer research questions that will inform the development of new products, processes, and organizations to deliver:

- More integrated procurement;
- Through a global supply chain; and
- Of economically, environmentally, and socially sustainable buildings and infrastructure.

Based on my analysis of the first 5 decades of research in our field, it is my strongly held view that CEM researchers need to broaden and deepen our frame of analysis. The new challenge is not just—or even mostly—about understanding, modeling, and optimizing costs in the construction and detailed design phases of construction projects anymore! The challenge for the next 5 decades is to conduct research that will help to maximize the lifecycle economic, environmental, and social value of the built environment over its lifecycle through an integrated global network of firms.

There is an associated educational challenge to educate "sustainable civil engineers" who are broadly educated and empowered system integrators with a focus on lifecycle, "triple bottom line" maximization of the value of our built environment!

There are three parts to this challenge. CEM researchers and educators must design and deliver research that helps the global construction industry:

1. Deliver buildings and infrastructure in a more integrated manner across their lifecycle—either through more vertically and horizontally integrated firms, or through long-term alliance partnerships;
2. Manage an efficient global project supply chain to deliver all of the product and service components for unique buildings and infrastructure that are deeply embedded in host country legal, social, and cognitive–cultural institutions around the world; and
3. Develop new kinds of products, processes, and organizations that will make the built environment of our children and grandchildren truly sustainable from a "triple bottom line" perspective.

More Integrated Delivery of Construction

Buyers of large construction facilities must currently deal with literally hundreds of specialist firms, or else hire an integrator to

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do this for them, which creates an extra layer of management. Most consumers would not choose to buy a car design from one company, an engine from a second supplier, a transmission from a third, a heater and air conditioner from a fourth, an entertainment system from a fifth, seats from a sixth, etc. Automobile companies play a design and systems integration role and provide lifetime services for maintenance and repair.

It currently takes way too long, and can be exceeding difficult—even downright unpleasant—to buy office space, manufacturing capabilities, housing, or public infrastructure. Practitioners and academics have focused on minimizing the first cost of construction outputs—as opposed to maximizing the value of customer outcomes. Is this an exaggeration? Ask any owner!

Drivers of More Integration

Several factors combine to demand a greater level of horizontal and vertical integration in the delivery of buildings and infrastructure.

Global Competition Requires Systemic Innovation

Innovation—the first driver of integration—is the most fundamental. One can find a long standing debate in the construction management literature about the extent to which our industry innovates. It is obvious to anyone who has worked on construction projects that the one-off nature of construction projects presents a never-ending stream of problems that require local incremental, innovation. At the same time it is clear that these incremental innovations are not systematically captured and diffused, even within single firms. However, the innovations that can have the most significant impact on productivity are systemic innovations—innovations requiring simultaneous changes by multiple interdependent specialty firms in the supply chain. Data on the diffusion of systemic innovations make it clear that they are extremely slow to diffuse through the United States construction industry.

The Ph.D. research of Professor John Taylor from the University of Texas, Austin presented a convincing analysis of why systemic innovations do not diffuse through a project-based industry like construction when all of the players on a project team are constantly changing from project to project. By using data from multiple countries, Taylor demonstrated that systemic innovations that cut across multiple trades can only be diffused through the industry when there is a relatively stable set of multitrade relationships among firms in the supply chain across multiple projects to capture the tacit learning required to successfully internalize, adopt, and reuse the innovation.

In liberal market economies like the United States, where there is a constant churning of the multiple consultants and contractors involved in projects, systemic innovations diffuse very slowly, thus greatly reducing potential productivity gains for the United States construction industry. In contrast, countries with more "coordinated market economies" like Finland or Japan foster long-term relationships between supply chain partners in the construction industry that create stable "quasi-firm" networks. These more stable firm networks can collectively learn over multiple projects how to diffuse complex, systemic innovations through their industries. The resulting productivity gains in the last few decades for the construction industries in some of these countries have been significant.

As construction becomes ever more global, firms based in liberal market economies like the United States, United Kingdom, and Australia will have to find ways to work in more integrated ways to compete successfully with the rate of construction innovation that can be achieved by companies from countries with coordinated market economies. More research on industry innovation through networks of firms can help to shed light on the costs and benefits of more integration in the delivery process of construction projects.

Infrastructure Development Requires More Integrated Project Governance

Governments in both developed and developing countries are finding it extremely difficult to raise tax dollars. Developing countries have virtually no formal economies to tax in order to create funds for infrastructure, and developed countries have demonstrated a lack of political will to tax themselves to pay for needed maintenance of their aging infrastructures. Private financing is an alternative to public financing, but it requires that the infrastructure sponsor set up new build–operate–transfer (BOT), build–own–operate (BOO), or other project finance business entities with more integrated governance structures that can integrate the construction industry's increasingly global supply chain for finance, planning, design, construction, and operation of the facility for terms that can range from 20 years to as long as 50 years.

Private–public partnerships to develop infrastructure through an integrated project delivery approach are working reasonably well to renovate infrastructure in developed economies, with some exceptions (e.g., the Euro Tunnel, which just entered the French equivalent of Chapter 11 bankruptcy). However, the long payback periods of these projects, in conjunction with the need for a strong rule of law to enforce contracts between the parties, pose serious challenges for the governance of "project companies" in emerging markets. In spite of political risk insurance, take or pay agreements, long-term supply contracts, currency hedging, and other attempts to use legal and contractual means for risk allocation, these projects have had, at best, mixed success with many very costly and highly visible failures in developing countries. The political and legal–contractual risks of funding a private–public partnership for an infrastructure project that would have to sustain its economic viability through multiple changes of government are simply too daunting for private investors in a country without a history of political stability and a strong rule of law.

Research to develop alternative funding methods and governance approaches for public–private financing of infrastructure in emerging markets is thus sorely needed.

Industrial Buyers Face Extreme Time-to-Market Pressures

Industrial buyers place ever higher value on time to market for their products. Manufacturing facilities are increasingly on the critical path to new product releases. In the case of fast-moving technologies like microprocessors, industrial buyers like Intel or Genentech deliberately wait until the last second to place their manufacturing equipment orders so they can minimize obsolescence of the equipment installed in their plants. Then they drive extremely hard to meet startup deadlines for production lines that can have gross margins exceeding \$1 million/h 7×24 during their early market windows!

Thus by delaying the start of their construction and accelerating its completion, these industrial buyers end up with a highly concurrent schedule that is extremely difficult to manage in a fragmented industry. Some industrial buyers like Intel have required their contractors and engineers to create more integrated design–build joint-venture companies to manage the complexity

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of extremely fast-track schedules, with only limited success to date. Inspired by Intel, Marriott, and others, the writer's research group conducted research during the 1990s on modeling and simulating project organizations engaged in fast-track project delivery to help design organizations that would be robust in the face of the very high supervision and coordination "hidden work" that this fast-track and extreme fast-track schedules generate.

Much more research needs to be done in this area to answer questions such as: How should the client organize its facility department and related contractors and consultants to buy fast-track construction? How can products, processes, and organizations be improved to permit effective modularization, prefabrication, and automation of semicustom design and manufacturing? What else can be done to deliver high-quality facilities of considerable complexity very fast?

Institutional Buyers Demand Better Buying Experience

Institutional buyers like hospitals, universities, or museums constantly struggle with finding better approaches for buying construction services. In many cases they do not have the kind of unitary, coherent leadership that a corporation has—a medical school or other university building may be the most extreme case of this "multiheaded monster" client. Moreover, some institutional buyers like churches or school districts develop new facilities intermittently, so it is difficult for them to develop and sustain high levels of in house capability to manage their internal facility development processes.

These are very challenging clients for our industry to serve. For example, our experience at Stanford is that the capital facilities group oscillates back and forth on about a 5-year cycle between purchasing construction in a more integrated way using contractors to provide various kinds of preconstruction services, versus a traditional design–bid–build approach in which contractors are excluded from the process until designs are completed. Neither approach turns out to be entirely satisfactory. Hence the oscillation! And both the internal staff involved in purchasing construction and the engineers and contractors with whom they contract often find the process to be both difficult and unpleasant.

There is a need for research on how to make the experience of buying construction both productive and delightful for these kinds of institutional buyers of construction. What does Nordstrom or Whole Foods Markets do differently than their competitors to develop such fierce customer loyalty through a more delightful buying experience? How could we adapt their winning strategies to the business of construction?

Barriers to More Integration

Public procurement laws that require a design–bid–build approach to construction have been blamed for fragmenting our industry? Yet the laws governing public construction in the United States and many other countries seem to be changing very fast. Design–build, BOT, BOO, and other more integrated approaches are being experimented with by many public agencies at all levels of government. The private sector seems to be lagging the government in many respects in adopting more integrated forms of delivery for construction.

What is impeding the evolution of better approaches? How can CEM researchers help to overcome these barriers?

Suggested Research on Facilitating More Integrated Project Delivery

Several kinds of CEM research might provide insights about how to increase the level of integration—real or virtual—in our industry. In all of the world's market economies, mature industries like construction have become progressively more locked in to "standard architectures"—i.e., the work packages into which all phases of the process are divided—for their products, and their industry supply chains have then fragmented accordingly:

- By project phase;
- By engineering discipline;
- By construction trade for contractors and workers; and
- By Masterformat specification code for vendors.

This extreme vertical and horizontal fragmentation of the construction industry's industrial structure has now become a "ball and chain" around the legs of the industry thwarting most attempts at systemic innovation. The evidence for this is the flat productivity curve for construction over the last 4–5 decades, compared to a doubling of productivity over the same period for all firms in the economy.

The prevailing product architecture and paradigm can only change through disruptive "systemic" innovations that overturn the current product architecture paradigm! What will be the disruptive paradigm for construction? Will it be related to new products, new processes, and organizations, or some combination of all three? This poses many interesting questions for CEM researchers interested in innovation and management of technology.

Taylor's research has demonstrated that vertical integration of the supply chain for construction—or "virtual vertical integration" through long-term partnerships among all of the specialty firms impacted by a given systemic innovation—dramatically accelerates the diffusion of systemic innovations through fragmented, project-based industries like construction. More work is needed in this area to understand the dynamics of learning in firm networks in our mature, project-based industry.

Addressing Challenges of Globalization

For our industry, the earth is not as "flat" as Thomas Friedman, the popular author and editorial writer for the *New York Times'* says it is! Construction is expanding globally as statistics on "foreign construction" over time from *ENR* and other sources report. At the same time, construction contractors have to be much more "deeply embedded" in foreign countries' local norms, practices, and legal systems than outsourced manufacturers or software developers need to be. Construction contractors entering a new foreign market must learn how to obtain multiple building permits in that country; recruit a local labor supply according to local labor laws; obtain customs clearance from local customs officials for materials and components; understand and meet local preferences for design features; and deal with a host of other unfamiliar local cognitive–cultural, normative, and regulative differences. They must also work in a network with literally hundreds of host country and third country firms, as well as nonmarket entities such as government agencies, nongovernmental organizations (NGOs), and other interest groups.

Challenges of Working across National Cultures and Institutions

"Unexpected transaction costs" of all kinds arise when working globally in cross-national teams and unfamiliar institutional environments. These transaction costs can be significant, reaching as high as 25% of project cost according to the work of Ryan Orr, director of the Collaboratory for Research on Global Projects at Stanford.

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National value differences of the sort described in the work of Professor Geert Hofstede and his colleagues are usually blamed for misunderstandings that lead to "unexpected transaction costs." But more recent research indicates that value differences are not the root causes of costs and delays on global projects. Differences in work practices, industry organization, and professional roles trigger "institutional exceptions." Once these exceptions have been triggered, differences in the national values and beliefs that Hofstede focuses on make it difficult to resolve these exceptions.

Needed Research on Globalization

Some early work has been done to understand the nature of these "institutional mismatches" and their cost impacts on projects, but a great deal more ethnographic and case study work can help to shed light on the causes of delays and cost overruns associated with global construction, and on ways to mitigate these challenges. In addition, research could be done on ways for global construction firms to capture and disseminate the lessons they learn through cross-national collaborations in different countries.

There are many pressures toward increased globalization. These provide important challenges for CEM researchers to address. Careful case studies of matched sets of global projects can help to shed light on the kinds of cross-national institutional differences that most often lead to problems. Once these problems have been identified, researchers can focus on identifying the best current practice in global project governance, or developing new governance structures for global projects that can help to mitigate these "institutional transaction costs" and that can maximize opportunities for cross-national learning.

By collaborating with colleagues in economics, finance, and political science, CEM researchers can begin to explore better ways to set up private–public partnerships, especially to develop infrastructure for the 1 billion new people who will be added to the population of our planet during the next decade, mostly in emerging market countries. Some of the most challenging research questions to be addressed in this area include:

1. What is the most sustainable project organization structure to perform infrastructure projects in various developed and developing economies—a BOT scheme, a concession, a management contract, or a full privatization—and how can these structures be enhanced with risk mitigation tools when they are not adequate as is?
2. What is the nature of the terms that need to be incorporated in the contracts between public and private parties ("shock absorbers" and "safety nets") to make them sustainable across multiple global business cycles and local changes of government?
3. How can we improve environmental, human rights, and dispute resolution mechanisms in multilateral and bilateral international treaties for global infrastructure projects in emerging markets? This issue is growing in significance as a new group of "south–south" investors have begun to finance large-scale infrastructure projects in resource rich countries in Africa and elsewhere, with nonexistent or minimal safeguards against corruption, and little or no assessment of environmental and social justice impacts of the projects they are financing.
4. What is the most effective role, and the most effective timing and extent of involvement, for all project stakeholders? This includes local populations who may not be direct or even indirect project beneficiaries, but who are potentially impacted by the construction and operation of new facilities.

Sustainable Development: Question of Balance!

A great deal of heat—but far less light—has been shed on the topic of "sustainability" of the built environment. Sustainability is a multidimensional concept that needs to be carefully conceptualized and even more carefully studied. In the writer's view, the way to achieve greater sustainability in developing the built environment is for CEM researchers to explore ways to achieve two kinds of balance:

1. Between the needs and desires of today's inhabitants of Earth versus the needs and desires of future inhabitants; and
2. Between the costs versus benefits—economic, environmental, and social justice—of new buildings and infrastructure accruing to different groups of stakeholders across their lifecycle.

Lifecycle economic cost analysis has been explored by researchers like Hendrickson and Horvath using input–output analysis techniques, and is relatively well understood by now. However, lifecycle analyses are seldom used to drive more sustainable decision making in our industry because the fragmented industry distributes the costs and benefits of projects to different participants across their lifecycles. In addition to understanding the integrated, lifecycle economic costs and benefits from an economic point of view, understanding and quantifying ecological and social equity costs and benefits of projects represents an exciting set of new challenges for CEM researchers.

It is well known that buildings consume around 50% of the energy used by developed countries, with attendant impacts on air quality, acid rain, ozone depletion, and global warming. Both urban and rural inhabitants consume huge quantities of water in ways that are not only inefficient, but are patently unsustainable. Californian farmers use heavily subsidized—essentially free—irrigation water to grow rice and cotton in semidesert environments, while farmers in tropical regions of the developing world that are far better suited to growing these crops struggle to compete against these subsidized farmers from rich countries, even in their home markets. Furthermore, Americans regularly irrigate their golf courses and fill their swimming pools with potable water of a higher quality than can be obtained—even in bottles—in countries like India or Mexico.

Given today's rising energy costs, the increasing evidence of global warming from CO_2 and other greenhouse gases, and desperate water shortages in many places, why is more attention not being paid worldwide to building more energy-efficient structures that use water more sustainably? The answers are becoming clearer over the last few years.

"Civil Engineers" versus "Environmental Engineers and Scientists"

Our profession is currently divided into "civil engineers" versus "environmental engineers." Many of the key early commitments in the lifecycle or construction projects are based on input only from financial sponsors, architects (in the case of buildings), and "civil engineers" who design and build their foundations and structures. "Environmental engineers" then attempt to address or remediate environmental concerns such as energy use, water (re)use, embedded carbon, indoor and outdoor air quality, and the like later in the process. Changes to siting, materials, methods, or technologies that could easily have been accommodated early in the project lifecycle—such as reorienting the building to improve its natural lighting and to optimize solar heat gain versus loss for

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that climate—become prohibitively risky and costly to address once loan covenants and building permits have locked in the original site plans.

NGOs, local political groups, and other advocates for environmental or social equity concerns related to construction projects often step in to raise issues even later in the process, when changes to the siting, scale, orientation, and scope of the facility are completely locked in and prohibitively costly and risky to change.

At these late stages, project sponsors naturally tend to dig in and oppose initiatives aimed at improving a project's environmental and social sustainability. Project sponsors are not necessarily opposed to sustainability goals; sponsors frequently share these goals. However, they will almost uniformly oppose late stage proposals for changes to siting, configuration, or other key attributes of a project to enhance its sustainability because such changes can pose threats to the entitlement or funding commitments already in place for the project.

Projects large enough to require environmental impact assessments at state or federal levels benefit from earlier involvement by multiple stakeholders and multiple design disciplines, but an overwhelming majority of construction projects do not benefit from this kind of multistakeholder, multidisciplinary early input. Thus, band-aid solutions that attempt to mitigate the "unsustainability" of such projects—e.g., adding extra insulation or solar photovoltaic panels to improve their energy performance—get patched onto buildings by "environmental and social engineers" who enter the process later.

Toward More Sustainable Built Environment

It is the writer's view that sustainability of the built environment can be vastly improved by CEM researchers who find new ways to bring multiple civil and environmental engineering perspectives to bear, along with the concerns of all involved project stakeholders, during the very early "shaping" phase of facilities.

The first step in this process is for the sponsors of projects to develop work practices and organizations that become more proactive in identifying all stakeholders with concerns related to the development of a given construction project and engage with them to get their input early. The benefit of getting input from all disciplines and stakeholders early rather than late is that it allows conceptual designs to be globally optimized early in the process at the lowest total cost, rather than optimizing around a small number of architectural and civil engineering issues and first cost, and then attempting to accommodate lifecycle costs, environmental concerns, and social equity stakeholder issues as modifications to a conceptual design that has been effectively locked in through early financial, legal, and regulatory approvals and covenants.

In place of "civil engineers" who make the early conceptual design decisions followed by "environmental engineers and scientists" and local political groups—or NGOs representing them—who attempt to patch their environmental and social equity issues onto these early conceptual designs late in the process, we need a new kind of CEE professional in the early shaping phases of the built environment. We need an "environmental civil engineer" or, even more broadly, a "sustainable civil engineer."

Some of the tools and knowledge necessary to educate sustainable civil engineers is currently available, but a great deal of research could be done to deepen and broaden knowledge, frameworks, and tools for more sustainable development of the built environment.

As stated above, a good deal of research has been done on lifecycle economic cost analysis. Gretchen Daily and her colleagues at the Woods Institute for Environment at Stanford have begun quantifying the value of "natural capital"—the economic value of environmental services provided by forests, wetlands, oceans, estuaries, grasslands, and even deserts. Less work has been done on quantifying the extent to which the built environment can provide environmental functions and services similar to those provided by the natural environment; for example, a dam provides some of the same kind of flood control and habitat environmental services as wetlands do, while decreasing other environmental services, e.g., restricting fish migration.

Systematic research to quantify the net economic value of environmental services could enable work on the magnitude and value of the net environmental services flowing from a given construction project. For example, the value of environmental services destroyed by a construction project that depleted forests or wetlands could be compared to the value of ecosystem services provided by the project (e.g., a dam provides flood control services, a water treatment plant provides denitrification services) in a systematic way. This would begin to allow lifecycle economic and environmental sustainability to be combined in a unified framework of net costs and benefits.

Bringing the third dimension of sustainability—social equity—into an overall cost–benefit sustainability calculus is much more challenging. Who bears the costs versus who receives the benefits of a particular project, and at which point in time, is inherently political. It reflects the strongly held and widely disparate views of various interest groups and their power structures in society, and is extremely difficult to reduce to one-dimensional quantitative metrics.

An approach to the governance of construction projects that balances these concerns has been incorporated into guidelines of the most progressive multilateral global developers such as the World Bank's International Finance Corporation. First, these guidelines require safeguards against corruption, which undermines social equity and reduces economic viability of construction projects. Second, their guidelines establish minimum standards for identifying and engaging all affected stakeholders early in the shaping phase of such projects, discussing, and debating the pros and cons of alternative project configurations—including the possibility of not building a project at all—explaining the rationale for all decisions, and setting expectations for measures such as resettlement procedures and levels of compensation. Since the early 1990s, the World Bank has established a series of independent "Inspection Panels" for its branches, including the International Finance Corporation (IFC), to investigate allegations from any group of two or more stakeholders who asserts that the Bank is not following its own guidelines.

Similar triple bottom line assessment guidelines and anticorruption safeguards have now been adopted voluntarily as "The equator principles" by commercial banks engaged in more than 75% of global project financing. Therefore approaches for the governance of global projects have improved dramatically over the last 2 decades. Going even beyond the equator principles, the notion of "prior informed consent" on the part of affected populations, especially indigenous groups with communal land titles, has now become enshrined in the constitutions of several developing countries, including Ecuador.

Clearly these approaches to project governance could be adapted and applied to private or private–public partnership projects such as urban redevelopment, mass transit, or near-coastal energy developments that pose the potential for economic versus environmental tradeoffs and require resettlement of exist-

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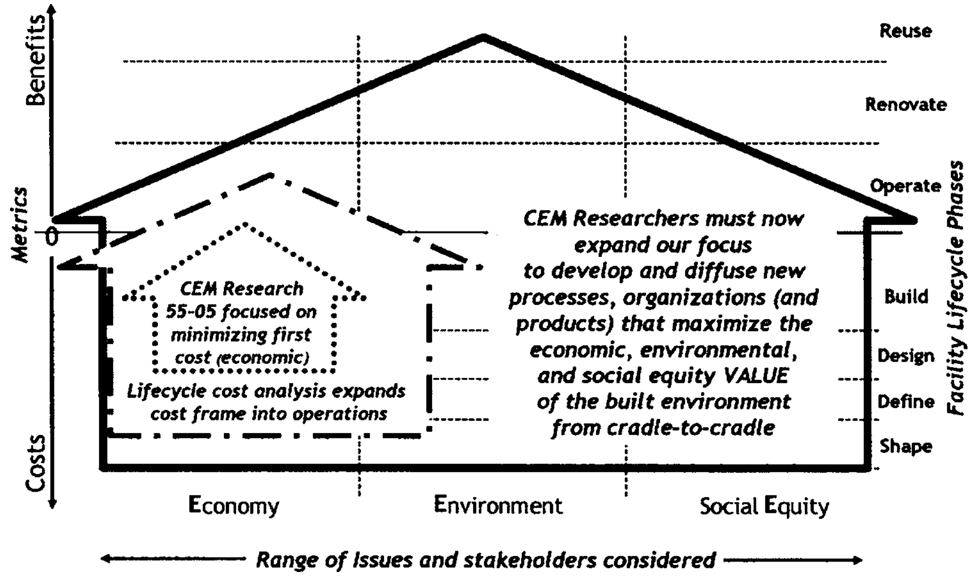

Fig. 2. Framing CEM research for next 50 years: maximizing economic, environmental, and social equity value of built environment

ing populations. Research in this area could study the effect of different project governance approaches for gathering stakeholder input and allocating costs and benefits continuously to different affected populations over the lifecycle of a project.

How CEM Researchers and Educators Can Promote Sustainability

To reiterate the challenge laid out at the beginning of this vision statement, CEM researchers need to broaden and deepen their frame of analysis. The new challenge is not just—or even mostly—about understanding, modeling, and optimizing costs in the construction and detailed design phases of construction projects anymore! The challenge for the next 5 decades is to conduct research that will help to maximize the lifecycle economic, environmental, and social value of the built environment over its lifecycle through an integrated global network of firms.

Fig. 2 summarizes graphically the ways in which we need to broaden and deepen our frame of analysis in choosing the kinds of research questions for us and our students to address in the next few decades.

Our challenge goes beyond conducting new kinds of research on ways to develop sustainable facilities, processes, and organizations over their lifecycles as described above. We must also challenge ourselves to redefine the knowledge base for our profession in our roles as educators and civic leaders. We must work to broaden and deepen the undergraduate and graduate curricula and the content of professional licensing examinations to prepare a new generation of "sustainable civil engineers." The new curricula for the professionals charged with developing the built environment must include:

1. Life–cycle economic cost and benefit analysis of facilities;
2. Ways to compute the net impact of new or renovated constructed facilities on the lifecycle value of environmental functions and services;
3. Methods and tools for carrying out multistakeholder identification, engagement, and negotiation processes; and
4. Understanding of, and experience addressing, the barriers to innovation in project-based industries, so they can successfully transform products, processes, and organizations in the construction industry.

Informed by our research on how to develop the built environment more sustainably, and armed with these kinds of new skills and tools, our profession can then begin to reinvent itself along the lines envisioned by ASCE's task force for the role of the civil engineer in 2025. "Sustainable civil engineers" who can bridge between traditional "civil" and "environmental" engineers will be "entrusted by society to create a sustainable world and enhance the global quality of life" for our children's children.

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