TOWARD INTEGRATED PRODUCT-PROCESS DEVELOPMENT: RESEARCH AGENDA FOR LIFE-CYCLE DESIGN AND SYSTEMS ENGINEERING FOR THE AEC INDUSTRY

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INTRODUCTION[1]

Today's construction industry is facing tremendous challenges. Up until 50 or so years ago typical projects were relatively simple; most of today's projects are complex. Advances in science and engineering have led to increasingly sophisticated understanding of physical and social processes, enabling more realistic modeling, computation approaches, and new means to physically realize a design. As a result, a myriad of new technologies and materials are now available to the builder. Projects therefore require the involvement of larger numbers than ever before of design-, fabrication-, construction-, as well as operation and maintenance specialists, each contributing necessary pieces to the product development process (Gil et al. 1999). Accordingly, our industry has become tremendously fragmented (Howard et al. 1989).

Specialists in the various disciplines have been able to optimize their own in-house operations by making strong assumptions about what others might do. As a result, failures of AEC systems today are usually not due to failure in work within the scope of any one specialty (e.g., calculation errors, selection of the wrong model, defective tooling, poor execution a construction method). The corollary, however, is that more and more failures are caused by poor handoffs between specialists or by one player making the wrong assumptions about work done by others (Tommelein and Gil 1999). Significant efforts must be devoted to coordinating and integrating all specialists' work (Tommelein and Ballard 1997).

Design and construction once used to progress sequentially and at a predictable pace but financial markets (esp. double-digit inflation rates in the 1970s) and ever-increasing global competition have made it necessary for numerous projects today to be executed on a fast-track schedule. This means that designers must complete design packages and release them for fabrication and construction prior to completing all their work. On the one hand they must make conservative assumptions about the remainder of the facility to make sure it will be feasible to meet the owner's requirements when the design is developed further. On the other hand they are asked to sharpen their pencils and avoid including what is seemingly unnecessary and costly.

In turn, increasing complexity and speed tend to inject project and process uncertainties. These must be recognized, then managed skillfully and with the proper tools. It will come as no surprise that project management tools (such as the critical path method) developed in the late

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1 A major part of this introduction was included in the proposal, co-authored by Iris D. Tommelein and Martin A. Fischer, proposing to the National Science foundation the organization of the "Berkeley-Stanford CE&M Workshop: Defining a Research Agenda for AEC Process/Product Development in 2000 and Beyond."

1950s-early 1960s when projects were fairly simple, slow, and certain[2], have not withstood the test of time. They are useful to project managers in addressing some aspects of their task, but only in a limited way. These tools are easily misused. Their shortcomings were made very clear in the 1970s and 1980s when legal claims throttled the construction industry. Consequently, AEC practitioners' attention shifted from performing and managing design, engineering, and construction to managing contracts and hedging their commitments in preparation for or in anticipation of litigation. This further promoted adversarial relationships that could only in a limited way be handled by means of partnering. These efforts do not advance the state of our industry and should be refocused on performing and managing direct work (Tommelein and Ballard 1997).

These project challenges and complexities require a rethinking of research issues and approaches for improving the competitiveness of the AEC industry. It is essential to note that this rethinking should not take place in a void. There is no need to reinvent the wheel. Many interesting concepts have been around for a long time and are described in the literature (if only there were time to read more...), but new technological developments make certain concepts more opportune to apply and implement today than they used to be.[3] The more fundamental research issues for our AEC industry lie in conceiving what products we want to produce and how we want to produce them. This engineering effort, concurrently addressing issues pertaining to the product and process, requires reliance on theory not only of science but also of production. This white paper argues strongly for research into and development of the latter as it has been sorely lacking.

WHAT IS CONSTRUCTION ENGINEERING AND MANAGEMENT?

It will be helpful to first clarify what is and is not comprised by construction engineering and management (CE&M). In this paper I use the term in its broadest sense. CE&M takes all aspects into account of the AEC product life cycle and span all of its processes including conceptual and detailed design, contracting, procurement, fabrication, transportation, construction, operation and maintenance as well as decommissioning. Many CE&M researchers and practitioners indeed adopt this systems view, which is so integrative in nature and critical to achieving overall performance. Other AEC practitioners are more focused. In order to make progress in their area of specialization, they must isolate problems and delve into the—often microscopic—details. CE&M adopts a much coarser view, abstracting away detail and often using more qualitative representations of the surrounding world rather than quantitative ones, so one can see the forest from the trees.

Another important distinction is that the CE&M researchers and practitioners are concerned with systems that usually include people and their idiosyncratic behaviors (!). By contrast those working on isolated problems work hard to eliminate people from their equations and experiments for that very reason.

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[2] Greg Howell (1998) characterized projects that are simple, slow, and certain as "stodgy" and projects that are complex, fast, and uncertain as "dynamic."

[3] For instance, the concept of hyper-linked documents came about in the late 1960s, but it took Apple Computer's HyperCard software in the 1980s and then the world wide web in the 1990s to allow this concept to really come to fruition.

Clearly, the two extremes are complementary—neither one can do without the other. Both practices and their associated research agendas must be pursued with vigor. The question then is how they ought to be pursued.

CE&M IS AN APPLIED AND ARTIFICIAL SCIENCE

CE&M is an applied science. Sciences such as mathematics, physics, chemistry, biology, materials science, etc. can be applied very well to the development of new products and building or environmental systems. Example outcomes are new materials and processes; instrumentation (including computers), tools, equipment (including automation and robotics[4]), and machines to work with them; connections and structural framing systems, water purification systems, etc. Insofar as these products and systems can be isolated esp. from people, they lend themselves well to laboratory or in-situ experimentation, and also of course to patenting and (international) trade. This type of AEC research is conducted by civil engineers such as geotechnical or structural engineers, environmental engineers, material scientists, mechanical engineers, electrical engineers, computer- and software engineers, etc. CE&M of course relies upon their findings as they must set up the appropriate production system to build the facilities to best meet the designer's intent as well as other objectives.

But CE&M must, because of its inherent breadth, also address the industrial engineering and business aspects of the AEC industry (which industrial engineers and business school people tend not to do). The study of CE&M must include the study of artificial sciences, that is the sciences pertaining to things that are created by people, such as design, economics, and management. The sciences of the artificial still are not acknowledged as ‘valid’ subjects of teaching in engineering schools to the extent they were recognized as needed and as was advocated more than 30 years ago by for instance Nobel prize winner Herb Simon (1969).

The AEC industry concerns itself with a product development process of one-of-a-kind facilities. It is unique in that regard from other manufacturing industries, and only a small part of the business world by comparison, though others may be striving towards such a high degree of customization. This identifies a niche for CE&M researchers to pursue.

A significant body of CE&M research focuses on project management, contractual relations, risk assessment, and use of information- as well as other technologies (e.g., bar coding, laser-based positioning). Some research has been conducted in areas such as process management and

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[4] Field automation for construction applications has been a well-funded area of research, especially in Japan in the 1980s (Tucker et al. 1991). It was claimed to provide a hedge against labor shortage (robots would either replace people or attract newcomers into a construction industry with more high-tech appearance), a means to improve safety, and a demonstration of technical ability when comparing firms against each other during prequalification. Many field automation efforts in Japan failed to be adopted in daily practice, however, though companies continue to develop new automata in order to maintain their technical know-how.

Research into construction automation and robotics in the US was also promoted in the 1980s (e.g., Ibbs 1987) but has slowed considerably in recent years because human organizational factors were said to stand in the way.

It can also be argued that automation (realized at a considerable expense) resulted in increasing production speed that could not be matched by other processes in the production system. What good it is strengthening one link in a chain if numerous other links are weak as well?

human and organizational behavior. A significant gap exists when it comes to developing understanding of the production system that underlies and drives (whether it is in a controlled fashion or not) the AEC product life cycle. Focused research in this area is sorely needed.

NEEDS ASSESSMENT

AEC researchers and practitioners need a theory of production management so they will be able to create better life-cycle designs and engineer their systems. Developing such a theory can be done by the CE&M community. Some have already started and called their new framework of conceptual understanding 'lean production[5].' Lean construction is just a name for this budding theory and significant shaping remains to be done.

Development of a theory requires: (1) theoretical understanding, (2) development of instrumentation, tools, materials, and processes to conduct experiments with, (3) experimentation to challenge the theory and refute it so new understanding will emerge.

THEORETICAL UNDERSTANDING

The CE&M community needs to sharpen its understanding of production systems and the associated physics (e.g., Hopp and Spearman 1996). It needs to increase its appreciation of uncertainty (including process and product variability resulting from different skill levels, human error, organizational behavior, motivation, among other things) and the impact it has on the system by creating models that explicitly acknowledge its existence. Researchers must team up with practitioners and set out to measure more system characteristics so the variables that drive our production systems can become better understood. In addition, we must also study human organizational structures in combination with production systems (e.g., Jin and Levitt 1996) for our conceptual understanding to become more comprehensive. We need to value the cost of human capital more, rather than treat people as interchangeable entities.

We need to study the literature of other disciplines and learn their physics, e.g., of industrial dynamics and feed-back control. "Industrial dynamics is a way of studying the behavior of industrial systems to show how policies, decisions, structure, and delays are interrelated to influence growth and stability. It integrates the separate functional areas of management---marketing, investment, research, personnel, production, and accounting... These five flows are integrated by an information network. Industrial dynamics recognizes the critical importance of this information network in giving the system its own dynamic characteristics." (Forrester 1961 p. vii)

For this new theory to be of greatest value, it will need to take into account the domain-specific engineering principles and processes that we have developed for AEC practice over the years. We must continue to teach our students these principles and processes in combination with production theory so the will truly understand their systems.

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[5] The International Group for Lean Construction “makes up a network of like-minded professionals and researchers in architecture, engineering, and construction (AEC) who feel that the practice, education, and research of AEC have to be radically renewed in order to respond to the challenges ahead.” (from http://www.vtt.fi/rte/lean/).

TOOL AND EXPERIMENTAL PROCESS DEVELOPMENT

Once a theoretical framework has been presented, tools and experimental processes must be developed to conduct experiments.

Especially worth noting as valuable tools for experimentation are new information technologies (virtual reality, CAD, simulation, spreadsheets, databases, GIS systems, wireless communication, palmtop computers, etc.). The significant body of CE&M literature focusing on the use of IT testifies to this but some reflects infatuation. There is ample reason to be excited about the opportunities provided for instance by web-based and wireless distributed computer systems but note that the excitement is not new[6]. The Business Roundtable (BRT 1983) pointed out that AEC practitioners have not used computers to the largest extent possible, and the same can be said today.

One should not forget that IT is but a tool (Hammer and Champy 1993 devote an entire chapter to "The Enabling Role of Information Technology"). We have powerful tools today and computer- as well as software engineers will continue to develop them. What we are lacking is the theory for our AEC domain in which to apply the tools. What are our production needs? What system behavior do we want to foster? Merely adopting tools for their own sake is not productive. Skepticism is in order regarding gigantic software systems such as ERP (enterprise resource planning) systems that appear to take over a number of companies. Operations must be designed first, then software tailored to meet the requirements.

EXPERIMENTATION

Experimentation is an essential part of theory development. Tools and instruments make measurements possible that may refute the theory. New, more comprehensive understanding can then follow with the formulation of a competing or subsuming theories.

It is difficult to duplicate experiments with actual companies on actual sites, and reproducibility is an important part of experimentation. Research should therefore be conducted into the development of better, more realistic modeling tools to aid in simulated experimentation. Modeling tools must be able to represent not only the geometrical CAD data that becomes available after a significant part of the design process has been developed, but also data that supports conceptual design, concurrent engineering, set-based design, etc. The further integration of product-oriented tools with process-oriented tools will also be very beneficial.

SUMMARY

The AEC community does not have a theory for production. A vocabulary to describe the industry's complexities with its numerous interdependencies and uncertainties is sorely lacking. Fundamental laws have not been articulated. Our community must adopt a systematic, scientific

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[6] "The appearance of high-speed electronic digital computers has removed the practical computational barrier...We have a tremendous untapped backlog of potential devices and applications. It is now to be expected that machine progress will stay ahead of conceptual progress in industrial and economic dynamics. Computing machines are now so widely available, and the cost of computation and machine programming is so low relative to other costs, that the former difficulties in activating a simulation model need no longer determine our rate of progress in understanding system dynamics." (Forrester 1961 p. 19).

approach towards conceptualizing its understandings if it wants to move away from its arts-and-crafts approach based on experience towards greater professionalism. This white paper recommends that the budding theory of lean construction, which presents a framework for improved conceptual understanding of AEC production management, appear at the top of the list of subjects in the CE&M agenda for further research and development.

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