FUTURE DIRECTIONS FOR COMPUTERIZED CONSTRUCTION RESEARCH

By C. William Ibbs,[1] A. M. ASCE

ABSTRACT: The crucial research needs and most promising directions for future computerized construction applications are the subjects of this article. It is a summary of the events and recommendations derived from a research workshop jointly sponsored by the University of Illinois Construction Engineering and Management Program and the National Science Foundation. The four principal theme areas of this conference were: (1) Project-wide data base and communication systems; (2) knowledge-based systems; (3) simulation; and (4) robotics, though many other peripheral issues were also discussed. Fifty leading representatives from industry, government and academia convened in Urbana, Illinois, to develop strategic plans for this research community to pursue over the next 5 to 10 years. Topics discussed included artificial intelligence, supercomputer simulation, autonomous robots, and project data bases that truly integrate design and construction. Though unanimous conclusions were rarely reached, enough consensus support was present to develop a strong, clear strategic plan of computerized construction research and to identify its constituent community. The participants also analyzed techniques for conducting better research studies and injecting more interdisciplinary and interuniversity cooperation into those programs.

INTRODUCTION

The American construction industry is facing enormous technological and institutional challenges and changes as it enters the last 15 years of this century. One very important instrument of such change is the computer and the models, computational techniques, and procedures that are adapted to this tool. For some time, researchers and practitioners affiliated with the industry have been discussing the various impacts of evolving hardware and software technologies. Most of these reviews have been of an ad hoc nature, however, with little coordination or even thorough understanding of all the activity in this field.

To provide a forum for information exchange as well as a mechanism to review research progress and needs, a U.S. National Science Foundation research workshop was held in Urbana, Illinois, May 19–21, 1985. Sponsored by the U.S. National Science Foundation and the University of Illinois's Construction Engineering and Management Program, this particular conference was focused on a narrow domain of research issues, i.e., computerized applications and procedures to construction. This paper reflects the basic flavor and tone of that meeting, as well as the recommendations and points of contention seen at the conference. A fuller discussion is contained in the Workshop Summary Report (2).

To those in attendance, the workshop was seen as an important milestone for the construction engineering and management research community. Of principle significance was the timely pause it provided for

[1]Assoc. Prof., Dept. of Civ. Engrg., Univ. of Illinois, Urbana, IL 61801.

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both principal investigators and research product consumers to review the progress attained to date and identify the most promising directions on which to embark for the next five years. This workshop also fostered insight into how this community should conduct its research with special attention devoted to mechanisms of increased coordination between the various research units. Another important offshoot was that attendees were able to discuss research proposal development and review strategies, a very important skill to hone for an academic discipline still relatively young.

Organization of Workshop

An important key to the success of this workshop was the formation of an advisory committee of experienced, knowledgeable leaders for each of the different topic areas reviewed. Some had even organized such affairs before. Four different topic areas were chosen for study: (1) Project-wide data bases and communications; (2) knowledge-based systems; (3) simulation; and (4) robotics. Because of the particularly wide range of issues encompassed by the first of these topic areas, two individuals were asked to serve as panel leaders; the other three areas were very capably administered by one individual each.

An organizational meeting was held in December 1984 to decide on such matters as program scope and format, the list of participants to be invited, and other pertinent issues. Selection of participants was predicted on two criteria: (1) Demonstrated competence in the area of academic research performance; and (2) demonstrated interest in applying or, at least indirectly, using such construction-related research. The end result was that 41 people attended the conference; 33 were academic researchers, 4 were leading industry practitioners, and 4 were representatives of major government research-sponsoring agencies.

At the organizational meeting, two special points were structured. The first was that two types of discussion sessions would be conducted at the conference itself: one would be small panel groups limited to approximately 10 people each with strict focus on a particular topic area, such as robotics. At these panel sessions the discussion leader and panelists would stake out the critical research issues of that field, scope viable research methodologies, and generate recommendations. The second type of discussion session would be a period for each small group panel to present its conclusions and recommendations to the entire audience. In return, reaction and critiques would be solicited. This dual-mode approach had the twin benefits of collecting the best ideas from a panel of experts while disseminating them to a large group of informed, interested people. Those recommendations were therefore subjected to a "test of fire" by the entire audience.

The second important point developed at this December planning session was that of "white paper" preparation. Each invited participant was assigned to a panel area and asked to submit a brief abstract of impressions regarding important research issues and on-going work efforts in that particular topic area. These statements were collected by the conference leader and distributed to the appropriate panel leader for integration and compilation. Twenty-six such abstracts were received and used by the panel leaders to draft a white paper for each of the individual panel areas. These 5- to 10-page statements thus served as a starting point for discussions at the workshop, and are available in the summary report.

In addition to exploratory discussion, periods were set aside during the two and one-half days of the workshop for interested parties to demonstrate computer software to the rest of the participants, regardless of its stage of development. The software ranged from a variety of simulation packages to several different knowledge-based expert systems. This was an enormously popular feature that provided a significant degree of interaction and cross-fertilization. The workshop itself began early on a Monday morning.

At the outset of the conference several underlying assumptions and specific goals were outlined. These were to streamline the focus of the discussions. First, the argument was advanced that the hardware- and software-design issues were only of peripheral consequence to this workshop. The actual thrust of the assembly was the identification and definition of scientific models, theories, protocols, etc., that used the computer as a tool, and that hold significant promise of advancing research related to the construction industry. Four specific goals were articulated:

1. Identify and, to an extent, structure the most promising avenues of computerized construction research for the next half decade.
2. Discuss with the attending government and industry representatives the practical implementation and application issues. This includes funding and other support issues so that these research and development products could be brought online to the industry more quickly and reliably.
3. Identify and develop the linkages between the four panel areas under analysis at the workshop.
4. Promote national and international collaboration on all aspects of construction-related research, not just computer-oriented issues.

With that basis, the workshop participants moved on to the individual panel sessions. The following sections detail the results of those deliberations.

Recommended Research Directions

Project-Wide Data Bases and Communications

This panel group was charged with investigating all important research issues associated with the development, use, and maintenance of project-wide data base and communication systems. The goal of such systems would be to provide an automated information repository to the principle project participants containing design, construction, cost, schedule, and other pertinent data.

Discussion of this topic began with one panel member's contention that current utilization of computers in construction management (CM) is nothing more than mere computerization of manual procedures. That is, the software has merely been adapted to the way we have always been scheduling or estimating projects, and that it is appropriate to rethink those problem-solving techniques. Though not all agreed with that strong premise, the panel considered it necessary to reexamine the fundamental underlying issues, needs, and constraints surrounding present-day construction management information systems.

Data in current CM systems are generally initialized during the construction phase rather than earlier in the project development. It was accepted that it will be more important in the future to link design-construction information exchange. This linkage should result in a greater reduction in total project management effort in contrast to the considerable effort now required to input and reextract the required information at each point in the design-construct cycle from conventional drawings and other paper documents. Computer-aided design (CAD) data bases were generally acknowledged as being a proper starting point for future development. However, the storage requirements necessary for such mammoth amounts of data led the panel to conclude that even though uniform data structures are necessary for information exchange (and good ones still remain to be developed), various distributed data bases will still be needed. These data bases will most likely be scattered between team members, and their in-house processors will operate on subsets of the total project data base. A global master data base, probably relational, will be needed to track and manage the information in the "purpose made" distributed data bases. Similar conclusions were recently made by the Building Board (1).

Concern was expressed about the processing power required to manipulate these large CAD data bases, especially in view of the expected artificial intelligence (AI) system requirements that will eventually merge with coordinated project data base systems. Given the expected advances in computer hardware and software technology, though, the panel decided that it is more important to resolve the issues surrounding a uniform data structure first. Once this long range goal is accomplished, technology can be found or developed to provide the necessary processing power.

In response to a challenge to define some of the attributes of the required data structure, one member suggested an object-oriented (sometimes incorrectly referred to as "frames") structure based on object-oriented languages. Such an approach allows more flexibility than current rule-based systems used for global representation. Object-oriented data representations are a recent development of computer science data base architecture research. Objects are generic entities and contain data as well as knowledge in the form of "slots" and "facets," respectively. Slots are repositories for data, while facets contain knowledge found in data and in the object itself.

For instance, characteristics of the slots, constraints on values, relationships to other objects including inheritance and the activation of algorithms, processes, and interobject messages would be examples of facets. Example objects may be "building" and "column." A column may inherit the attribute "made of reinforced concrete" from the building, since column exhibits a "part-of" relationship with building. When a specific instance of the generic object is invoked, it will acquire the predefined attributes of the object with only unique data and knowledge to be added. Because relationships can be explicitly defined, unlimited hierarchies can be constructed.

Good development environments for object-oriented systems already exist in the AI field (e.g., OPS, SRL, KEE, ART). Object data bases can be interfaced with traditional data bases to preserve existing software systems such as the CAD/CAM system. One panel member noted that this field could probably benefit from a study of that segment of the manufacturing industry that uses the manufacturing resource planning (MRP) model with complex hierarchical data bases. Object-oriented models were also noted as offering a checklist compatibility in the definition of slots and facets. This will be important in checking for errors and omissions.

Some felt that the real problem in this area lay in the different views and types of data that are required to be communicated among the different project members. An important issue in the minds of many was the identification of the characteristics of the information itself and the information flow between project team members. These attributes should be studied to determine the content and relationship between the elements. It was pointed out that the construction industry, while now highly fragmented, will probably change in structure to allow greater integration. The necessary standards to achieve integration definitely need research and development.

An underlying prerequisite for the development of such standards (preferably voluntary guidelines) is a greater understanding of the data requirements and cognitive processes in each phase of the design-construct cycle. The panel reasoned that ideally a neutral representation can be found that keeps the cognitive processes separated from the data (possibly a three-dimensional model with temporal information). Such a rich but neutral model would offer maximum flexibility as process requirements change. One panel member referred to this as "communication between, rather than integration of" and hence a mapping is required between the various data formats needed by the major project team members. Essentially this discussion pointed out that research is urgently needed in identifying the information the various project participants need, in what format, how it will be utilized, what the generic objects are, and how they are related.

Graphical project data representation was considered next. Present-day CAD systems lack the capability to react to and convey knowledge about the representative objects. Further, many other types of information are necessary, e.g., temporal (schedules), monetary (cost), and interrelationships. A discussion ensued during which several possible data representations and attributes were mentioned. The conclusion was that any data model should be hierarchical and based on generic entities, containing knowledge about aspects such as time-cost, the relationship to other physical and nonphysical entities, and the format of communication between these entities. The Open Systems Integration Model (OSI) of the International Standards Organization (ISO) was proposed an an example of the hierarchical nature of such a required model. CM research should define what must be the various levels of this model.

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A discussion followed that highlighted the complexity and vast amount of knowledge required for a realistic, totally integrated data model. One example presented the design choices for the generic object "CHILLER." A change in the CHILLER may or may not change the water supply capacity, structural loads, electrical loads, installation strategy, and even R-rating of windows and insulation materials. It appears that these generic objects, of which a very large number will be needed, will have to be provided with a template of the knowledge elements most likely to be encountered. Human decision making is expected to handle exceptional cases. Another proffered example highlighted the iterative nature of design and estimating where the same generic object acquires a succession of increasingly accurate attributes, all of which are interrelated to some degree.

Concern was expressed at this point about the rapidly escalating volume of data and the difficulty of capturing explicitly the knowledge that is now held by all members of the project team. One aid is that data input can be minimized by associating much generic data with the input of symbolic items. Photogrammetry and pattern recognition were mentioned as possible ways to reduce data input as well as increase accuracy. It was recognized at this point that a globally accessible data representation is indeed a long-term goal, but as one member put it, "we need to know where we are going." Short-term goals should be developed, which in parallel and succession could bring the industry to this final goal.

Based on industrial needs, one of the more important goals suggested is the development of a data representational form, minimizing the reinput of data in the design-construct cycle. Drawings should not be eliminated, but rather should be by-products of a knowledge-based project model. Research into the requirements of the major users of blueprints constitutes an immediate need. It was noted that some more sophisticated CAD vendors are currently pursuing more intelligent systems that, in fact, are based on object model representation.

As the panel concluded its first session, the consensus was that an initial research goal should be to test the applicability of various data representations, especially object-oriented data models. A warning was issued that the representation may look good but fail due to the organizational dimension, something very difficult to capture. It was also observed that to understand the information flow between the project participants, a better understanding of the relationships linking those project participants has to be developed, i.e., how the information flow changes depending on whether the relationship is organizational or contractual. Further discussion pursued in a general way the research needs to make a project data base system amenable to future expert systems development work and robotics implementations.

During the final working session the panel developed research topics that can be broadly classified into two categories: data representation and storage; and information flow and utilization. The first category includes research into such topics as: (1) Appropriate representations of different types of data, including graphic and nongraphic. Object-oriented representations seem promising for some types, but other representations should also be investigated; (2) generic objects, their attri-

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butes, and the impact of time upon them; and (3) development of a data model that will allow efficient mapping between information used and contributed by project participants. This representation scheme has to be rigorously tested and validated.

The second category of needed research includes: (1) Study of the information flow network. Identification of the information crossing organizational boundaries, the required format and confidence levels, and the utilization of the information at each node of the design-construct cycle. The organization perspective definitely needs to be included; (2) interdisciplinary data mapping of standards, or flexible communications protocols; and (3) data capture (especially implicit data capture) and screening or validation methodologies within the appropriate contextual dependencies.

The recommended approaches are to first tackle a large project as a prototype in an attempt to represent it in object-oriented form. In parallel, work on resolving some more fundamental questions should proceed. For instance, what information is required, in what format, and what knowledge content is optimally/minimally required?

An intermediate goal was defined as follows: In view of the urgent needs of the industry, the long-term goal should be reached via useful short-term goals. Immediate research is required to ease the burden of duplication of effort. Systems should be further developed and electronic document exchange investigated more. Other issues of merit included processors and models to test data representations for completeness and robustness, and methodologies to document and codify information flow, role, and responsibilities, as well as the required dependencies.

Knowledge-Based Systems

The knowledge-based systems panel attempted to evaluate the potential of artificial intelligence concepts and their specific applications to construction engineering and management problems. The panel discussion was broken into several different topic areas: (1) definition of knowledge-based systems (KBS); (2) application areas for KBS; (3) tools for building KBS applications; (4) the art of building KBS (knowledge acquisition); and (5) philosophy for guiding research on KBS.

The KBS panel began its deliberations by assessing and distinguishing between knowledge-based expert systems (KBES), knowledge-based systems, and expert systems (ES). An ES was defined as a computer system that contains some particular human expertise (surface knowledge) and that is based on heuristics or rules of thumb. A KBS is viewed as being founded on knowledge of physical processes (deep knowledge) and hence may be considered a superset of ES. A system that combines both surface and deep knowledge is a KBES. At this early stage of construction engineering and management applications, KBSs were chosen to be the tool of initial development.

Deep knowledge is understood to comprise basic principles, e.g., physics or chemistry, and in terms of humans is that knowledge used by an individual having, e.g., a bachelor of science degree in civil engineering. On the other hand, surface knowledge is mostly heuristics or general rules of thumb that evolve from the experience of repeatedly

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solving the same or similar types of problems. For instance, the type of learning that an auto mechanic acquires from rebuilding automatic transmissions over time would be surface knowledge. A mechanical engineer understanding the principles of fluid motion and gear ratios would be held to possess deep knowledge.

Given these premises, the minimum attributes that differentiate a KBS from any other traditional algorithmic computer program were then enumerated: (1) Explanatory capabilities ("glass box" versus "black box"); (2) flexibility to view and modify knowledge over time; (3) symbolic inferencing (manipulation of facts or concepts rather than just numbers); (4) language independence (i.e., written in any programming language); (5) data context driven (order of rule execution depends upon data supplied during consultation); and (6) rules have only local knowledge; control structure chains rules together based on data supplied.

Discussion then turned to the range of possible research applications involving applications of KBS technology. The applications discussed by this panel are grouped by type of knowledge, degree of structure in the knowledge, and suggested implementation tool. The relationship between these different dimensions is summarized in Fig. 1.

The following outline itemizes construction tasks that are suggested as appropriate areas of KBS implementation. Rather than extracting each application, the panel decided to sketch only a few examples for each category. This list is by no means complete or exhaustive.

1. Classification/evaluation problems: (1) Safety evaluation; (2) claims evaluation; (3) selection of contractor or selection of construction methods; and (4) selection of equipment, leasing versus buying.
2. Monitoring/forecasting: (1) Cost control or total project performance measurement; (2) equipment performance; and (3) generation of input to existing algorithm (computer program) and interpretation of their output.
3. Planning/design: (1) Risk identification; (2) site layout; and (3) conceptual design of building.
4. Diagnostic: (1) Building diagnoses and repair; (2) project risk or status evaluation; and (3) lifecycle operation decisions.

Type of knowledge	Surface knowledge ... Deep knowledge
Degree of Structure in knowledge	Structured Selection ... Generation/Planning
Implementation Tool	Reasoning language .... Representation Languages
Type of Application	Classification .... Monitoring ... Planning Evaluation .... Forecasting ... Design Interpretation... ... Scoping

FIG. 1.—KBS Application Spectrum

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5. Qualitative simulation: (1) Design sensitivity analysis; and (2) risk analysis in bidding.

6. Interpretation across varying levels of data accuracy: (1) Signal interpretation of: nondestructive testing; combination of data from many sensors; detection of bad data; and automatic forecasts as checks against manual prediction; and (2) maintenance planning and scheduling: outage management; and opportunistic repair.

Applications can also be grouped by size of problem domain with which each is able to cope. For instance, narrowly scoped problems where state-of-practice lags state-of-the-art infers that reasoning languages seem to be a better solution technique. On the other hand, problems requiring general capabilities and deep knowledge demand knowledge acquisition and tools that are more flexible. Hence, planning and design problems will take longer to develop.

The uses of KBS have specific advantages over other more direct decision support systems. For example, they can be useful in training personnel on company or technical procedures. KBS can also be useful in integrating different modeling procedures across different disciplines (mechanical, electrical, and structural). The systems are also valuable for formalizing existing knowledge and identifying gaps in the knowledge as potential areas for future research.

Many tools currently exist within the broad field of computer science, which offer potential for civil engineering researchers to build KBS. These tools can be categorized into three groups: (1) General languages (LISP, PROLOG, C, FORTRAN, . . .); (2) representation languages: low level (OPS, SRL, etc.) and high level (KEE, ART, PSRL); and (3) reasoning languages (EMYCIN, INSIGHT, DF, PC, etc.) The panel agreed that each of these groups of KBS languages has a well-defined set of particular applications. For instance, reasoning languages are very well suited for narrow problem domains. Representation languages, on the other hand, are designed for more general systems and require the use of deep knowledge, but ultimately will probably prove to be more useful.

The LISP language was generally agreed to be a very useful symbolic language, but one with limited numerical computation capabilities. This of course has major implications to civil engineering researchers who will be designing systems that interface between both qualitative and quantitative simulation. Moreover, the language is a hard language to read, and a difficult language to understand. PROLOG, though widely used, is even less flexible than LISP.

On the other hand, with OPS, each user must build his or her own inference mechanism. Knowledge is represented in an IF. . .THEN fashion. In case of rule selection conflict, OPS provides the user with a "rule conflict solver" to decide which rule to fire first. OPS, as well as LISP, has very limited numerical computation capabilities.

It was agreed that tools implemented in a personal computer environment can be used to prototype possible applications and identify possible extensions. These probably would be suitable, in fact desirable, for more limited scope problems. However the complexity of construction will undoubtedly lead to many systems being developed and regularly used at the higher end, especially as the cost of this higher-level technology drops and the operational familiarity by users grows. Already many institutions, including the University of Illinois, have acquired Symbolics-class AI machines to conduct prototype development.

One of the most perplexing questions facing this panel was the issue of what to do when multiple experts differ on the solution to a particular problem. There is, naturally, no one answer to this dilemma. Suggested as possible remedies was the policy that a series of alternate KBS should be generated rather than one consensus KBS. This allows the user the flexibility of selecting the system that appeals to him the most, moreover, quantitative techniques such as fuzzy set theory and bayesian logic may help in this regard of selecting the best KBS. Behind this proposed suggestion is the assumption that it will be possible to evaluate and validate all expert views.

When the panel's deliberations were presented to the entire audience, several concerns were expressed. First, that knowledge-based systems are the panacea for all problems confronting the industry. Development of such systems to solve meaningful problems will take time. Moreover, an outshoot of this concern was that KBS might be seen as "black boxes" by the end users who in turn misuse the system because they fail to understand the underlying assumptions and the scope of the problem domain. That concern was generally assuaged by noting that every legitimate KBS will contain an explanation module, thus the end user can trace the line of reasoning followed to arrive at the solution reducing their mystery.

Civil engineers and researchers in this field should direct their attention to both representation and reasoning languages for their product development efforts. The reasoning tools can be used widely for classification problems. However, more sophisticated types of problems such as conceptual building design do not work well within a reasoning tool environment. "Rule induction languages" were observed to be essentially decision table processors. This is adequate for many construction problems but cannot be the only system bases for the industry.

A final concern was that in the eyes of industry practitioners a KBS has some mystical quality about it. Doubt was expressed about the immediate acceptance of such systems by the industry. A counter argument raised was that the construction industry eventually accepted computerized CPM and other project control systems, albeit very slowly, yet their usefulness goes without question today. The panel members and a majority of the audience felt that ultimately knowledge-based systems will find widespread application within the construction industry.

In conclusion, a suggested list of research topics was developed by the principals. This agenda was developed on a time-scaled basis with a number of short-term projects, a few intermediate-term projects, and one or two large long-term projects. Under the short-term category it was suggested that lower end tools be used to solve classification, evaluation, and interpretation problems. Among these types of research projects are the following goals: (1) To gain user acceptance and developer ability; (2) to discover and improve techniques for civil engineering knowledge acquisition; and (3) to identify appropriate validation techniques.

On the intermediate-term basis, use of qualitative simulation as a means to conduct risk analysis and to evaluate the impact of personnel decisions on the life of the company or even just the project were seen as two major contributions of this technology. On a longer-term basis, more system integration is envisioned; first, conceptual and detailed design and planning systems were encouraged. The emphasis in these types of development processes should be on interdisciplinary systems that address cost, constructibility, quantities, building codes, and CAD graphics. Integrated decision support for construction projects was also identified as a rich area for development. Such systems would address the cost, schedule, resource demands, uncertainty of data associated with project planning, and hopefully integrate such back into better design. Finally, a goal of developing more user-friendly high-end tools was specified. The panel looked to leading users such as the Corps of Engineers, Department of Defense, and the National Aeronautics and Space Association (NASA) as being prime sponsors in this regard.

Simulation

The panel charged with discussing the various multifaceted aspects of simulation evaluated the models and algorithmic procedures, both mathematical and nonmathematical, that are generally recognized as being simulation concepts and tools. Of particular concern here were issues of human-machine interaction, integration of site-developed information, and innovative data acquisition and processing techniques.

The panel started with several basic assumptions. First, it is crucial to place better information into the hands of the people who need it, in a quicker and more timely way than we now do. At the same time, we must be careful not to overload the doers of work with too much information. For that reason, better interpretative tools are necessary, such as graphics, speech synthesis, and data reduction in order to allow the doers to visualize the recommendations and output of the simulation exercises.

Secondly, the panel argued that there is a strong need to develop a lexicon to improve the communication between the different parties of a construction project. This in turn will provide much needed relief to a fragmented construction industry. It was also recognized that CAD data bases and computer communication tools must contribute in the future towards gluing together the parts and people that make up a construction project. Such communication links can help mitigate the change and dispute problems due to defective design and construction practices.

The panel identified three definite tasks and types of people commonly involved in a typical site or project operation: the planners; the doers; and the controllers. The planners must identify with the doers to design more efficient construction methods and site layouts and work ahead with their computers to develop more efficient strategies. The panel questioned whether computers are as useful for the doers as they are for the planners and what the consequences would be if that question were answered affirmatively. The answer, it was argued, can be found by searching the hierarchical computer applications at the operation level.

That is, simulation can be used at three levels: the process level; the project level; and the corporate level.

After considerable discussion of these starting premises the panel was able to summarize their concerns for needed research into a table (Table 1). In addition, they were able to identify whether the work remaining to be done was of a research, development, or implementation nature. The panel members also identified instances of strong linkages between the work in this particular topic area and work in the other three panel areas that were part of this conference.

The first issue identified by this panel was that of creating and enhancing data collection tools for analysis technologies. Monitoring and controlling input resources to sustain production is certainly an area that deserves new research. This normally involves capturing data on input resources, analysis using various simulation tools, and a feedback loop to the system to improve its efficiency. New simulation models would be welcomed by researchers though their development is probably secondary to the broadening and simplifying of existing simulation techniques. Research was suggested as needed to define ways to make these modeling systems friendlier. Possible directions include more graphics, image and pattern recognition, and speech synthesis. To some extent the developments in the broad field of artificial intelligence were projected as being adaptable to this general field, too.

Also discussed at this time were some of the new ideas and advancements in simulation techniques in modeling. Mathematical and operations research theoreticians working in the broad field of simulation have certainly moved beyond the early GPSS models on which many of the construction simulation packages are based. However, marginal benefits gained from these newer generation simulation algorithms are still awaiting proof that they justify the extra effort and cost of adaptation for construction.

A second subject area investigated by this panel was that of the human and organizational aspects of modeling and simulation. A major problem in today's construction industry is lack of support staff (low overhead crisis). A comparison was provided with the Japanese construction industry where more staff as well as more elastic work rules help the doers generate better work plans. A definition of computer hierarchy needs for the doers must be established for the typical firm. The question was raised as to whether the doers are so involved in their day-to-day affairs that they ignore the benefits of learning how to use the computer. To some extent this seems true. Conversely, concern was raised whether too much is being expected of computers and computer packages by the planners. Along the same line concern was also expressed whether computers can be overused by the doers.

A related issue discussed involved simulation of the decision and judgment making carried out by higher level management. Successful applications have been developed for managerial training (e.g., AROUSAL). A close relationship with research in the expert system areas was recommended. More tools have been developed and implemented in the behavioral sciences, such as business management, than in any other field. An important challenge for the construction industry is to integrate the different levels of simulation such as the operational models

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TABLE 1.—Breakdown of Main Issues and Analysis of Resulting Elements

Approach (1)	Description (2)	Linkage (3)
	(*a*) Issue 1: Creating and Enhancing Tools—Data Collection and Analysis Techniques	
Re	Monitoring and control of input resources to	Db
	sustain production	Ro
Re	Methodology of construction site simulation	Db
De		Ro
Re	Broadening and simplifying existing simulation	
De	tools	
Re	Simulation at: process level	
De	project level	
	corporate level	
Re	Simulation as operational tool	Ro
De	Problem solving in real time	Es
Im	Progress	Db
	(*b*) Issue 2: Human and Organizational Aspects of Modeling and Simulation	
Re	Staff and tools to support doers	
Im	Cost-benefit analysis	
Re	Planning/control/doing	
Im	Define hierarchy of computer needs for doers	
Re	Simulation at higher level management:	Es
De	—Teach theoretical concepts	
Im	—Deal with management's qualitative environment	
	—Role playing	
	—Highlight gaps	
Re	Simulation as operational tool	Es
De	Problem solving in real time progress	
Im		
De	Define relationships	Es
	Field people—computers	
De	Need of human interface/computers	
Im	Simulation to support strategical decision making	Es
	(*c*) Issue 3: Interface among tools and applications	
Re	Design and construction error detection, control, and analysis	Es
Re	Merging top/bottom and bottom/top planning	
De	Interface between boundaries of tools	
Im		
De	Fragmentation of industry	Db
Im	Data base interface	
Im	Information to right people at right time	Db

Notes: Re = research; De = development; Im = implementation; Es = expert systems related; Db = data base related; and Ro = robotics related.

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and the organizational or corporate packages.

The integration of all the planning tools at the disposal of the firm is important from the corporate level down to the operational level. Additionally, a universal lexicon is necessary to improve communications at and between each of these levels. The problems caused by industry fragmentation can be alleviated with the use of computers and communication systems via development and implementation of data base interfaces and CAD systems. Still the problem of getting the right information to the right people in a timely fashion is profound. It is felt that the computer is a useful tool in this regard, though.

Another facet of this interface issue is design and construction of error detection, control, and analysis. Suggested research was needed to help improve mechanisms to avoid, control, and learn from errors in both design and construction stages. To some extent expert systems research will help in this regard. Still, this general problem area would seem to be amenable to the probabilistic and risk assessment approaches offered by simulation modeling.

The panel next examined the role of supercomputers and minisupercomputers in the construction industry. These very fast, mainframe machines and minis are coming to the attention of researchers in the application fields like construction today. Their principle benefit is a parallel processing architecture, which allows concurrent digestion and analysis of information and data. Some individuals took the position that such machines are a step backward toward the large centralized mainframes of 20 years ago. If true, this would be contrary to the direction that benefits most field managers and engineers today. Others, however, argued that the distributed parallel architecture is a crucial point of these machines and that eventually this data base architecture will migrate down to the personal desktop computer.

It seems likely that some success will evolve from this approach because operations will be modeled at a much deeper level than ever before. The collapse of massive amounts of data into simple, intelligent forms will also probably result. The resulting recommendation, not universally agreed upon by all members of the panel, was that some dedication and attention should be devoted to studying these parallel processor architectures. At the fundamental level, the question of which types of construction problems and techniques are amenable to such modeling is a good first question awaiting an answer.

In a wrap-up discussion, the panel speculated about a "war-room" scenario in which the major participants of a construction project could cloister themselves as one element of a planning procedure in advance of the project kick-off. Supplementing this sequestered group would be access to specific simulation tools and artificial intelligence packages. They then could plan the project to a level of detail never before achieved. Such a war-room concept would benefit from linkage from the expert system and project data base concepts described earlier. It would, of course, also require all sorts of external data (e.g., economic indexes, labor quality and availability, weather, commercial pricing, etc.) that we in the industry currently make gross assumptions about.

Because of the size of the benefits projected to arise from such a cooperative planning approach, it is reasonable to expect the industry to move in this direction during the next 5 to 10 years. This most likely would first start with large centralized owners who have a repetitive type construction in their capital budgeting programs. The panel endorsed this approach.

In concluding, this panel noted the general field of simulation is a much more mature field than the others discussed at this conference. The field has benefited from the use of some of its tools in actual construction practice. As a consequence, many of the promises held out by the group's research recommendations seem to be more tangible than those proposed by the other areas. However, it must be remembered that the field of simulation itself was once in its infancy and has grown to assume a significant role in planning and evaluating construction operations and management decisions.

Robotics

The purpose of the robotics panel was to define the basic research issues surrounding robotic applications to construction. Scope included viable applications; basic technological issues like sensing, mobility, control, and system integration; and ancillary issues such as safety, industry acceptance, socio-economic concerns and design for constructibility.

Clearly Carnegie-Mellon University is the leader in construction-related robotics research at this time. However major strides are being made by other institutions, such as the Massachusetts Institute of Technology (MIT) and the University of Illinois. Companies such as Caterpillar Tractor Company have also begun to investigate the potential of this concept.

An initial question addressed by the panel was what differentiates a robot from an intelligent machine or automated factory process. The critical attributes of a robot were generally agreed to be mobility, autonomy, capability to deal with large forces, and the (cognitive) ability to cope with dynamic, unstructured, harsh environments. Moreover, robots must rely on a sensing-control loop to process information from a project data base, generally in a rule-based fashion. Overall, the participants agreed that they could recognize a robot upon sight, but not necessarily describe one very well, especially in contrast to the current generation of intelligent machines, e.g., laser-guided road pavers and undersea pipelayers.

The panel next examined why robots would find a place in construction. The consensus was, in order of priority, that motivation will stem from: (1) Increased productivity and subsequently more attractive economics; (2) improved safety with robots assigned the more hazardous tasks; (3) sheer additional brute strength; and (4) enhanced construction quality. These particular functions and their order of priority are important issues to this research field because they give direction to designers of both robotic hardware and software systems.

It was pointed out that many mechanical and electrical engineering laboratories around the country have worked quite hard to develop simple robots. Except for pedagogical purposes, however, they generally have little application to the construction industry. Construction robots must be able to overcome problems such as tripping on electrical cords and bouncing off walls, as well as deal with much greater forces. These early attempts, however, do represent the necessary first step of developing prototypes into more mature technology.

Industry's involvement in robotic research development will naturally be largely a matter of economics. Economic feasibility and value constraints in this area of research are probably more important than in any other area discussed at this conference because of the amount of money involved to conduct this research. Representatives of industry did volunteer to provide some training and equipment assistance.

Pressing research issues needing academic attention at this time were grouped by the panel into four broad categories:

1. *Concept/feasibility* includes such issues as cost effectiveness, improved productivity, quality control, and technological feasibility.
2. *Basic technology* determines the special needs of construction and examines the various options. Problem areas include sensing and interpretation, manipulators and effectors, environmental impact, mobility, and control.
3. *Demonstration*: The industry is a hard-sell and without working demonstrations support will be limited. These demonstrations initially must be limited in scope to very specialized and skilled tasks, hence, the selection of such prototypes will be crucial.
4. *Scale* issues include scope of robotization as well as level of autonomy. The Japanese have chosen very small and simple problem domains. Autonomy in a domain should begin at the lowest level with increased sophistication coming as experience is gained.

In addition to the direct technological concerns looms the issue of institutional change. This was a sentiment expressed very strongly by the industry representatives in attendance. Many aspects of robotic-based construction will differ from conventional construction technology. The problem is how, where, and when the changes will occur. There will be a fundamental rethinking of the entire design process as robots move into the workplace. Immediate economic concerns tend to force the view to the microlevel or to one of tailoring the individual equipment components and materials to suit the robots. The macrolevel view, nevertheless, needs to be investigated concurrently.

There are many technological issues with which to deal concerning design and constructibility. For example, what degree of conformity and productivity will society approve? Will construction workers readily accept their new workmates, and can they be retrained to operate and maintain robots? Moreover, should a new union classification be formed—robot tender—to perform this function? Will this workforce then be supervisory or employee based? Many other issues fall into this general category of socio-economic concerns.

The panel agreed that robotics research is basically only about five years old. From that visionary plateau, they proceeded to set forth an agenda of research needs for the next five years (i.e., next generation). This agenda was structured on a three-tier basis, from large system undertakings down to research project investigation; see Fig. 2.

Many important issues remain to be addressed and resolved in this area. It was recommended that one of the first tasks incumbent upon

Tier I: Large System Undertaking

1 (one) Large integrated effort like a Sputnik program:

- Space Construction

Funding by NASA or DOD, or a Construction Manufacturer's consortium.

Cross-disciplinary research with both basic and applied efforts.

Tier II: Several Large Project Endeavors

6-10 "System" level projects such as:

- Robotic earthmoving and material handling system
- Hazardous waste handler
- Pre-casting plant

Joint Industry-University research or mission agency funding

Tier III: Research and Development of Specific Individual Application

Many traditional Principal Investigator/Research Assistant Projects such as:

- Flexible manipulators
- Large force strategies
- QC/Sensing systems
- Post tensioning

NSF, mission agencies, entrepreneurial efforts. More basic research than other two tiers.

FIG. 2.—Construction Robotics Research Agenda

the construction research community is to develop an archive of information on construction robotics and robotics-related issues. Ideally, this archive would be a centrally located facility that might offer online computer access. There have been some expressions from officials of various national research organizations that the development and archiving of such information data bases is an important task that they are willing to support at this time.

It was also foreseen at this conference that construction robotics will have such a fundamental change on the industry that more than just hardware and software specialists need to be involved. Sociologists, labor economists, architects, product manufacturers, and other specialists will have important input about the future of robotics-related issues.

The final point of agreement on the issue of robotics at this conference was that there will be rapid and fluctuating rates of change in the research progress made. Construction robotics are currently in an embryonic state; however, most of the knowledge developed by researchers in other disciplines (e.g., mechanical engineers with automated manufacturing processes) will be major reference sources of information for researchers in this field. It is difficult to anticipate what may happen in this decade. In large part maturation of robotics will be largely dictated by development in the other three workshop areas and even some yet to be discovered.

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Summary and Conclusions

Summary Issues

This section represents a meta-summary of the most significant points that evolved from the workshop. It is neither a substitute for nor a repetition of the individual subject sections. Still, some comments of an overview nature are appropriate, especially as the four topic areas relate to each other.

Probably the key finding that developed from this conference was the degree to which all of these topic areas relate to each other. Foreseeable at the outset of the event was that there were some relationships between the four different areas, but the magnitude was underestimated by virtually all conference participants. As may be obvious from the earlier discussions in this paper, the division of the workshop theme into four target areas was more for convenience of discussion than for any other reason. These boundaries were often exceeded and reliance on parallel developments in the other three areas was clearly expressed by each of the different panel leaders as the workshop unfolded.

Many of the participants expressed the opinion that the data base group was the unifier of all four areas. It is certainly easy to see the interrelationship between the topic areas when viewed from that particular perspective. For instance, a project performance forecasting expert system would definitely have to take into account the amount and type of work done to date, as well as that remaining (as stored in the project data base). Planning exercises involving simulation tools would necessarily rely on an efficient, comprehensive data set, and, as discussed before, so would intelligent, autonomous robotic systems.

The interaction is certainly two-way, though. Clearly the types of efficient data storage schemes envisioned here will need a machine-order intelligence (knowledge-based system) to remedy the bane of large data bases: execution slowdown resulting from inefficient data structures. Similarly, the sensing unit of robots will have to provide real time environmental and performance information to a simulation module to allow the robot to learn better work methods. If one believes that input/output transfer is really the main bottleneck to getting faster run-times, whether for robotic applications or large-scale project data bases, then parallel processor technology may well be the most fruitful area for research and development over the next several years.

The key to encouraging interrelated research programs that will help move ahead all four of the areas would appear to be major, multitask research endeavors, e.g., a space station project. Though it seems counter to prevailing political philosophies, some federated endeavor with sponsorship beyond a single firm may be the most viable direction. Perhaps an innovative moderate scale project initiated by a trade association, whether user- (EPRI) or builder- (AGC) oriented, is this research community's best hope.

Clearly the research community must establish a strategic plan to move from where we are now to the utopic state spoken of by many of the workshop participants. Several grand plans were discussed, but the one that drew the strongest support was inspired by Paul Teicholz. That vision is shown in Table 2 as a time-scaled plan of execution. Naturally

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TABLE 2.—Long-Term Strategic Plan for Computerized Construction Research

Research topic (1)	Timeframe: Short term (2)	Intermediate term (3)	Long term (4)
Project-wide data bases	Extract quantity data from CAD data base	Replace plans and specs as design end-product; make them by-products	Add knowledge components to data base to facilitate communications flow, etc.
Expert systems (KBS)	Simple diagnostic system; stand-alone; structured	Multiple objective; context dependent; middle management problems; integration with data bases	Built into control systems; part of design process; adaptive
Simulation and modeling	Ease of use; graphic input and output; "what if" capability	Integration with planning and control systems and project data bases	Integration with robotics
Robotics	Identify payoff areas; solve repetitive problems	Modify construction practices where desirable; introduce in less constrained problem domains	Integrate with project data base, KBS to allow greater automation

the immediate research efforts should be small-scale individual undertakings with initial dedication expended to the most promising projects as identified throughout this paper and conference report. Inspection of this grand plan reveals, not surprisingly, that as this community moves further along in time, the research will eventually come together in the wholistic fashion described. The challenge to the construction research community will be to exploit the synergistic potential available from uniting these separate puzzle pieces.

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Appendix.—References

1. Building Research Board, National Research Council, *The 1984 Workshop on Advanced Technology for Building Design and Engineering*, 1985, 83 pp.
2. Ibbs, C. W., *Proceedings of a Workshop for the Development of New Research Directions in Computerized Applications to Construction Engineering and Management Studies*, Construction Research Series Report No. 19, Univ. of Illinois, July, 1985, 126 pp.

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