UILU-ENG-85-2009

Civil Engineering Studies
Construction Research Series No. 19

ISSN: 00694266

PROCEEDINGS OF A WORKSHOP FOR THE DEVELOPMENT OF NEW RESEARCH DIRECTIONS IN COMPUTERIZED APPLICATIONS TO CONSTRUCTION ENGINEERING AND MANAGEMENT STUDIES

C. WILLIAM IBBS, JR.

The University of Illinois at Urbana-Champaign
Department of Civil Engineering
Construction Engineering and Management

Prepared Under Contract No. CEE 84-17681
for the National Science Foundation

JULY 1985

PREFACE

The American Construction Industry is facing enormous challenges and institutional changes as it enters the last 15 years of this century. One instrument of this change is the computer and the models, computational techniques and procedures that we adapt to this tool. For some time researchers and practitioners affiliated with the Industry have been discussing the various impacts of evolving computer technologies, both hardware and software. Most of these reviews have been of an ad hoc nature 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 review of research progress and needs, a U. S. National Science Foundation Research Workshop was held in Urbana, Illinois on May 19-21, 1985. To those in attendance the Workshop was seen as an important milestone for the Construction Engineering and Management research community. Of principal significance was the timely pause it provided for both principal investigators and research product consumers to review the progress attained to date and the most promising directions to embark on 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 research units. Another important offshoot was that attendees were able to discuss proposal development and review strategies, a very important skill to hone for an academic discipline still relatively young. This report is an attempt to capture the sense and recommendations of that conference.

To the readers of these proceedings, one crucial point is repeatedly stressed throughout. Namely, that a comprehensive study of these recommendations is essential to obtain a balanced and complete understanding of what transpired at this Workshop. The four topic areas that formed the crux of this conference were, to some extent, arbitrarily defined. That is, there are tremendous interrelationships between all which can best be grasped by understanding the progress achieved to date and recommendations for future undertakings in every one of these four topic areas. Undoubtedly, the next five years will see other developments that we did not anticipate. Such changes are the best reason to conduct another workshop sometime in the intermediate future.

This author, who served as Workshop Coordinator, received valuable assistance from a number of individuals and acknowledges their input. First, a debt of gratitude is extended to K. C. Crandall, R. E. Levitt, B. C. Paulson, Jr., and D. R. Rehak who drafted the white papers, led the panel discussions and reviewed these proceedings with rapidity and thoroughness. D. Echeverry, J. De La Garza, F. Grobler, J. Kim and D. Wall served as panel recorders and contributed heavily to the preparation of this summary report. The assistance of J. Melin and B. Reuter in all aspects of the Workshop is also noted and appreciated. Finally, I would like to acknowledge the contribution of Le Bayer who served as a panel leader and co-principal investigator for this project. Too few people realize the value of his contributions.

This material is based upon work supported by the National

Science Foundation under Grant No. 84-17681. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author and do not necessarily reflect the views of the National Science Foundation. Gifford Albright, of the Structures and Building Systems Program, is Program Director, and his generous support is most gratefully appreciated.

Questions or comments about the many issues raised in this summary report should be directed to the author.

TABLE OF CONTENTS

LIST OF TABLES

WORKSHOP PROCEEDINGS

CHAPTER 1

INTRODUCTION

This report is a summary of the various discussions and events that transpired at a Research Workshop held May 19-21, 1985 in Urbana, Illinois. The theme of the Workshop was "Development of New Research Directions in Computerized Applications to Construction Engineering and Management Studies." It was sponsored by the U. S. National Science Foundation and organized by Professor C. William Ibbs, Jr. of the University of Illinois.

The organization of these proceedings has an intentional and specific structure. To best understand the recommendations that have come from that Workshop, the reader, at the very least, should review the specific chapter closest to his or her interests, Chapter 6 and the relevant white papers (Appendix A). To do otherwise is to risk losing the true flavor and thrust of these proceedings. In that spirit, the main body of this report has been written succinctly and editorial opining minimized.

Evolution of an Idea

Research workshops have been conducted in the past for the Construction Engineering and Management research community. They, however, were neither as narrowly focused as this workshop nor targeted to computerized applications. Those two points, especially the first, were keys to the success of this meeting.

Choosing the specific theme of computerized applications was not difficult. This author simply noted what was really the central, pressing issue for this research community in terms of activity and opportunity. Without a doubt, that was computer applications. It did take some organizational effort to settle on the panel areas of: 1) project-wide databases and communication systems; 2) knowledge-based expert systems; 3) simulation of construction operations; and 4) robotic applications. In fact, these areas have begun to blend together so much that the demarcations were almost arbitrary. That interdependence is underscored by the discussion of Chapter 6.

The next step was to develop and submit a brief, clear proposal to NSF. Gifford Albright, Program Director of the Structures and Building Systems unit, was very helpful with advice.

Organization of the Workshop

Upon approval of this Workshop proposal, an advisory committee of experienced, knowledgeable leaders in the different topic areas was assembled. These people were Le Boyer of Illinois and Keith Crandall from Berkeley (project communications and databases); Bay Levitt, Stanford (knowledge based systems); Boyd Paulson, Stanford (simulation); and Dan Rehak from Carnegie-Mellon University (robotics). An organizational meeting was held in December 1984 in Urbana to decide on program scope and format (Appendix B), list of participants to be invited (Appendix C), and other issues.

At that meeting, two crucial points were structured. First, two types of discussion sessions would be conducted at the conference. One would be small panel group discussions, limited to about twelve people each, focusing strictly on one topic area; e.g., robotics. In 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.

The second important point developed at this December planning session was that of "white paper" preparation. The invited participants were assigned to one panel each and asked to submit a one or two page abstract of their impressions regarding the important research issues and on-going work efforts in that particular topic area. These statements were collected by the conference chairman and distributed to the respective panel leader for integration and compilation. Twenty-six such abstracts were received and used by the panel leaders to draft a white paper for their individual panels. These five to ten page statements then served as a starting point for discussions at the Workshop. <u>These white papers are contained in Appendix A and also should be read very carefully by the reader, especially if the reader wishes to develop a research proposal from them</u>.

The Workshop informally began on Sunday afternoon, May 19, with a reception and software demonstration period. During this time participants were invited to demonstrate software products, in whatever stage of development. An IBM PC and an IBM PC/AT were made available for this purpose. Also, a video recorder/player unit with color monitor was installed on-site. This was used to display a variety of robotic research at Carnegie-Mellon University, and to relate the experiences of Professor John Slater in bringing an expert system tutorial into a structural design course at M.I.T. Two similar demonstration periods were made available on Monday for the same reason. During this second day, a LISP-based supermicro computer workstation, suitable for advanced artificial intelligence research, (a Texas Instruments "Explorer") was installed on-site permitting complex expert system shells and products to be demonstrated. This was an enormously popular feature of the Workshop and provided a significant degree of interaction and cross-fertilization. Appendix D is a listing of those software products that were exhibited and several others that were not because of machine unavailability. Interested parties can contact the listed individuals directly for further information.

A welcoming address and set of goals was presented by this author at the Workshop's official start, Monday morning. At that time, the argument was advanced that the hardware and software-design issues were only of peripheral consequence to the Workshop. The actual thrust of the assembly was the identification and definition of scientific models, theories, protocols, etc., that use 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 included funding and other support issues, so 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; and

4) Promote national and international collaboration on all aspects of' construction-related research, not just computer-oriented issues.

From that basis, the Workshop participants moved to the individual panel sessions. The next four chapters document the discussions that transpired in those small group sessions, the reaction to their recommendations by the assembly as a whole, and the closing summation. Chapter 6 represents a summary of the entire proceedings and offers several independent suggestions.

CHAPTER 2

PROJECT DATABASES AND COMMUNICATION

The Project Database panel was charged with investigating all important research issues associated with development, use and maintenance of a project-wide database and communication system. The goal is to provide an automated information repository to the principal project participants containing design, construction, cost, schedule, and other pertinent data.

1. PANEL DISCUSSIONS

At the outset the two panel leaders suggested that the first session be devoted to brain storming, building from the contents of the panel white paper. A discussion ensued which was sparked by a panel member's remark that current utilization of computers in Construction Management (CM) is in fact mere computerization of manual procedures. As a result, the panel considered it necessary to re-examine the fundamental underlying issues, needs and constraints.

While data in present CM systems are initialized at the construction phase, it was accepted that it will be important to link the design-construction information exchange more closely in future systems. This should lead to a great reduction in total effort, since considerable effort is now required to re-extract the required information at each point in the design-construct cycle from conventional drawings and other paper documents. The question was then raised whether CAD databases may and even should serve as a starting point for further development. It was generally acknowledged that they should.

The practical implications of such implementations were discussed next. A discussion of the storage requirements led to the conclusion that even though uniform data structures are required for the exchange of information, various distributed databases will still be needed. These databases will be scattered between project team members and their in-house processors will operate on subsets of the total project database. A global master database, probably relational, will be needed to track the information in the "purpose made" distributed databases. (Similar conclusions were reached by the Building Research Board (BRB) 1984 Workshop[1].)

Concern was expressed about the processing power required to manipulate large CAD databases, especially in view of Artificial Intelligence (AI) system requirements. Given the expected advances in computer hardware and software technology, the panel decided that it is most 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 by a panel leader to define some of the attributes of the required data structure, one member suggested it should be object-oriented (sometimes referred to as "frames") and based on object oriented languages. (This approach was explained and discussed at length later in the session.) Another member added the

[1] Building Research Board, National Research Council, The 1984 Workshop on Advanced Technology for Building Design and Engineering, 1985.

characteristics of the information flow between project team members are an important issue. These attributes should be studied to determine the content and relationship between elements. In the discussions that followed it was pointed out that the Construction Industry, while now fragmented, will probably change in structure to allow greater integration. The necessary standards to achieve such integration definitely need research and development.

An underlying prerequisite for the development of standards is 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 should be found which keeps the cognitive processes separated from the data (possibly a three dimensional model with temporal information). Such a rich but neutral model will offer maximum flexibility as processes and requirements change, because it is unbiased. One member called it "communication between" rather than "integration of," and hence a mapping is required between the various data formats needed by the individual project team members.

Graphical project data representation was considered. Present-day CAD systems lack the capability to react to and convey knowledge about the represented objects, it was concluded. Furthermore, many other types of information are necessary, e.g., temporal (schedules), monetary (cost) and interrelationship. A discussion followed during which several possible data representations and attributes were mentioned. The conclusion was that the data model should be hierarchical and based on generic entities, containing knowledge about aspects such as time, cost, their relationship to other entities and format of communication between entities.

The OSI (Open Systems Integration) model of the ISO (International Standards Organization) was proposed as an example of the hierarchical nature of the required model. CM research should define what the various levels of its model should be.

A discussion followed which highlighted the complexity and amount of knowledge required for a realistic, totally integrated data model. One example presented the design choices for an incidence of the generic object "chiller." A change in a "chiller" may or may not, for example, change the water supply capacity, structural loads, electrical loads, installation strategy, and R-rating on windows and insulation material. It appear s that 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, though not necessarily all. Human decision making is expected to handle the exceptional cases. Another 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 escalating volume of data and difficulty of capturing explicitly the knowledge that is now represented by all the 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 a means of reducing data input, as well as achieving feedback; e.g., as-built drawings. It was recognized that a globally acceptable 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 immediate goals suggested should be the development of a data representational form minimizing the re-input of data in the design-construct cycle. Drawings should not be eliminated but rather be by-products of a knowledge based project model. One member added that research into the requirements of each user of drawings constitutes an immediate need.

At the second session's beginning, the panel reviewed some of the capabilities required in a global data representation and then briefly considered rule-based systems. One panel member felt that rule-based systems are too complex and inflexible for this task, and that only object oriented representations offer the required capabilities. (Although object oriented representations dominated the discussion during the rest of the session, it appeared that most panel members felt that other representations also warranted discussion, had time permitted.)

A panel leader then invited a short tutorial discussion on object oriented data representations. 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 about the data and the object itself. For instance, characteristics of the slots, constraints on values, relationship to other objects including inheritance and the activation of algorithms, processes and inter-object messages would *be* examples of facets. Example objects may be "building" and "column." A column may inherit the attribute "made-of-reinforcedconcrete" from building since column exhibits a "part-of" relationship with building. When a specific instance of a generic object is invoked it will acquire the predefined attributes of the object, with only unique data and knowledge to be added. Because relations can be explicitly defined, unlimited hierarchies can be constructed.

Good development environments for object oriented systems already exist in the artificial intelligence field (e.g., OPS, SRL, KEE and ART), and object databases can be interfaced to traditional databases to preserve existing software systems.

A panel member noted that CM can possibly benefit from a study of the manufacturing industry which uses the Manufacturing Resource Planning (MRP) model with complex hierarchical databases. He added that the object oriented model also offers a checklist capability in the definition of slots and facets. This will aid in checking for omissions.

Some of the issues discussed earlier were then reviewed in terms of object oriented presentations. It was reiterated that the real problem lay in the many different views of data which were required and how to communicate that data between project members. Some members of the group felt that standards were necessary, otherwise a communication scheme will become too expensive. Others expected standards to produce stagnating constraints. Further discussion unified these views with the conclusion that flexible, evolving standards are necessary and that standardization will be driven by economic forces.

This discussion once again emphasized the necessity of a greater understanding of the underlying issues of the information flow process --what information do the various project participants need, in which format, how is it to be utilized, what are the generic objects and how are they related? All these are considered urgent research issues.

At this point the belief was expressed that CAD and graphics models are so important to potential near term solutions that research in these topics should not be neglected in favor of the more fundamental issues. Another member mentioned that CAD vendors who are pursuing more intelligent systems are in fact basing further development on the object model.

One of the panel leaders then asked for suggestions of short and long term research goals. The first suggestion was to proceed with the design of a database for a building based on the object oriented data model. Some panel members felt that so much work is necessary to resolve the underlying questions that it would be premature to start with such a database design exclusively. After it was noted that such implementations often drive the required basic research in an efficient manner, the panel agreed that both top-down and bottom-up approaches in this research discipline were necessary.

Cast in a more general form the panel decided that a first goal would be to test the applicability of the object oriented data model. Later it was broadened to include other representations. A panel member warned that a representation may look good but fail due to the organization dimension.

The second goal is to increase our understanding of the information flow between project participants. Answers are needed to questions such as what communication links are required; are they a function of' organizational or contractual structure; what do they need to know and in what format(s). It was suggested that tools should be developed (or borrowed from other disciplines and adapted) to capture and document this communication process.

A third area identified is how and where expert systems will be used to improve decision making, and even if this research area can afford to wait on the maturation of another. Fourth, research is required in the long term to make databases accessible to robotics implementations.

The scheduled time for the session ran out as the discussion turned to deterministic vs probabilistic views of data and problems.

2. LARGE GROUP PRESENTATION AND AUDIENCE RESPONSE

The panel leaders started with a brief summary of the earlier panel discussions. Emphasis was given to the panel's exploration of the elements of the overall integration of data. As the final goal a Construction Utopia was depicted where information with semantic content can flow transparently between project participants. The importance of intelligent data representational models, object oriented or knowledge based, was also highlighted. Comments were then invited.

The first reaction was a restatement that global integration of databases may be prevented or frustrated by the real world of contractual partitioning between project participants and the climate of' legalism.

It was pointed out that the Woodshole Workshop on Advanced Technology for Building Design and Engineering[2] sponsored by the Building Research Board had been working in the area of databases and communication and had explored many of the issues already. (The report of the Woodshole Workshop became available one week after this NSF Conference was held and contains valuable material relating to this topic.)

Work at Carnegie-Mellon University on object oriented databases, in a Smalltalk Programming environment, revealed that this type of database has the same general features as those used in CMU's robotics development. The speaker recommended that research be initiated on finding a strategy to interface various databases in a flexible manner. In so doing it is important to know what systems do (the underlying processes) and not only what they look like.

Another speaker elaborated on the difficulty of communication between systems due to the amount of knowledge required and subtle organizational factors. An example of such a difficult-to-achieve requirement is the anticipation of the impact of design errors.

A panel leader mentioned that the panel discussed the checking of omissions and boundary values in terms of the object model for deter-

---

[2] Building Research Board, National Research Council, The 1984 Workshop on Advanced Technology for Building Design and Engineering, 1985.

ministic as well as probabilistic approaches. An open discussion of capturing data ensued. One panel leader added that the anticipated system will provide a useful service by reducing overall project cost, and that the project participants should therefore be willing to bear the additional cost of data acquisition and processing.

The discussion of interorganizational communication continued with the observation that object oriented representations are useful to analyze the communication process. Two panelists elaborated on the need to establish the actual process and content of communication in view of organizational factors and added that it is a research area in need of immediate work.

Some felt that the established body of research in general organizational theory is adequate, and that the implementation of a system for inter organizational communication should proceed. A respondent argued that general theories cannot be applied to CM directly, and have to be adapted and tested in the construction environment first. Work on the mixed market model by the Swedish economist Gunnar Mydal seemed appropriate to this problem.

Standardization of information flow between project participant was discussed next. A panel leader stated that it is essential to minimize the re-input of data during different phases of the project. This led to the question of tolerances. The same object, rebar for example, is viewed with different tolerances by the designer and fabricator while it is normally ignored by the concrete estimator in terms of displaced concrete. It was eventually agreed that the problem is actually one of identifying the appropriate context from which tolerance considerations can follow logically and automatically.

Because more computer input will be generated, it was anticipated that more errors could enter the system. It will therefore be essential to develop intelligent ways of screening the input automatically. One contributor summarized the required research as "what information crosses organizational boundaries, what format is needed and what confidence level required." Another stated that encouraging results are obtained as AI screening systems are placed closer to the point of input, and he considered research into knowledge based screening of input another important research area.

One individual considered it futile to attempt to determine what is presently being communicated since systems change people's requirements. The solution, instead, is to develop a flexible protocol structure.

The session concluded with a discussion of the interface between traditional and object oriented databases. The question was raised whether existing databases (representing a large investment) can evolve towards object oriented databases. A panelist responded that efficiency dictates a variety of databases for different applications, and some of these probably will not evolve towards object databases. However, object databases will have to be capable of referencing traditional databases and representing relationships between various elements.

3. PANEL SUMMARY

During the final working session the panel developed research topics which can be broadly classified into two categories: data representation and storage, and information flow and utilization.

The first category includes research in topics such as:

- Appropriate representations of different types of data, including graphic and nongraphic data. Object oriented representations seem promising for some types of data, but other representations should also be investigated.
- Generic objects, their attributes and the impact of time upon them.
- Development of a data model that would allow efficient mapping between information used and contributed by various project participants. This representation scheme should be rigorously tested and validated.

The second category includes:

- Study of the information flow network. Identification of the information crossing organizational boundaries, the required formats and confidence levels and the utilization of the information at each node of the design-construct cycle. These studies should include the organizational perspective.
- Interdisciplinary data mapping standards or flexible communication protocol.
- Data capture (especially implicit data capture) and screening or validation methodologies within the appropriate contextual dependencies.

The recommended approaches are:

- Tackle a large project as a prototype and attempt to represent it in an object oriented form.
- Work in parallel on resolving the fundamental questions (e.g., what information is required, in which format what knowledge content is optimally/minimally required).

An intermediate goal was defined as:

> In view of the urgent needs of the Industry, the long"term goals should be reached via useful short term goals. Immediate research is required to ease the burden of duplication of effort. CAD systems should be further developed and electronic document exchange should be investigated.

Other issues of merit are:

- Processors and models to test data representations for completeness, robustness.
- Methodologies to document and codify information flow, roles and responsibilities and the required dependencies.

The reader is reminded that this is not an exhaustive list of deserving research topics in the area of databases and communication. The topics above are merely those which the panel discussed during the limited time of the working session.

CHAPTER 3

KNOWLEDGE-BASED SYSTEMS

The Expert Systems (ES) panel consisted of fourteen researchers representing private business, government, funding agencies, and universities. Additionally, there were several researchers who made significant contributions to the white paper yet were unable to attend the workshop. Thus, the reader is encouraged to carefully review the thoughts and ideas mentioned in the white papers as well as the contents of this summary. Its scope was to evaluate the potential of Artificial Intelligence (AI) and the specific applications of the various concepts embodied in the field of AI to Construction.

1. PANEL DISCUSSIONS

The panel met for a total of four hours during which time an aggressive agenda was covered. The panel developed its research recommendations based on the following discussion areas:

Subject 1: Definition of Knowledge-based Systems (KBS);

Subject 2: Application areas for KBS;

Subject 3: Tools for developing KBS applications;

Subject 4: The art of building KBS (Knowledge Acquisition Methods);

Subject 5: Standards for testing and validation of KBS;

Subject 6: Philosophy for guiding research on KBS.

Subject 1: Definition of Knowledge-Based Systems (KBS)

The panel began by assessing and distinguishing between Knowledge-Based Expert Systems (KBES), Knowledge-Based Systems (KBS), and 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 upon knowledge of physical processes (deep knowledge) and hence may be considered a superset of ES. One that combines both surface and deep knowledge is a KBES.

Deep knowledge is understood to comprise basic principles, e.g., physics or chemistry, and in terms of humans, it is used by an individual having, for example, a Bachelor of Science in Civil Engineering. On the other hand, surface knowledge is mostly heuristics or rules of thumb, which evolve from the experience of repeatedly solving the same or similar types of problems. For instance, the type of learning that an auto mechanic acquires over time from rebuilding automatic transmissions.

Given these viewpoints, the minimum attributes that differentiate a KBS from any other traditional computer program were then developed:

- explanatory capabilities ("Glass Box" vs "Black Box")
- flexibility to view and modify knowledge
- symbolic inferencing (manipulation of facts or concepts rather than numbers)
- language independence (i.e., written in any programming language)
- data/context driven (order of rule execution depends upon

data supplied during consultation)

- rules have only local knowledge; control structure chains rules together based on data supplied.

It was accepted by this panel that if a KBS is developed in a LISP or higher level AI language environment and then recoded as a procedural program in FORTRAN, the resulting system is no longer considered a KBS. That is, it has lost its flexibility for the underlying knowledge to be modified. Yet, through a control structure, they combine intelligently.

Subject 2: Application Areas for KBS

Discussion then turned to the range of possible research areas involving applications of the KBS technology. The applications are grouped by type of knowledge, by degree of structure in knowledge, and by suggested implementation tool. The relationship between these dimensions is summarized in Table 3-1.

The outline below itemizes some construction tasks that are suggested as appropriate areas for KBS implementation. Rather than abstract each application, the panel decided only to sketch a few examples for each category. The reader is advised to consult the white paper for more detailed descriptions of potential applications. This list is by no means complete or exhaustive.

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

Table 3-1 KBS Application Spectrum

CLASSIFICATION/EVALUATIOM

- safety evaluation
- choice of foundation type
- seismic hazard
- claims evaluation
- selection of contractor
- selection of equipment; lease vs buy
- to bid or not to bid
- selection of contractual form and elements
- scheduling network analysis
- selection of construction methods

MONITORING/FORECASTING

- cost control or total project performance measurement
- equipment performance
- generation of input to existing algorithms (programs) and interpretation of their output

PLANNING/DESIGN

- construction methods/plans
- contract clauses
- risk identification
- contract documents
- technical specifications
- site layout
- work methods
- conceptual design of buildings

DIAGNOSTIC

- project status evaluation
- building diagnoses and repair
- life cycle operation decisions
- repair/replace/do nothing situations
- project risk

QUALITATIVE SIMULATION

- risk analysis in bids
- design sensitivity analysis
- choose construction methods

INTERPRETATION ACROSS VARYING LEVELS OF DATA ACCURACY

- signal interpretation
  - non-destructive testing
  - combination of data from many sensors
  - detection of bad data

    - automatic forecast as checks against manual predictions

- maintenance planning and scheduling
    - outage management
    - opportunistic repair

Applications can also be grouped by the size of domain with which each is able to cope.

a) Narrowly scoped where state-of-practice lags state-of-the-art. Reasoning languages seem to accommodate this type of domain better (classification and evaluation).

b) General capabilities requiring deep knowledge. Tools for implementing these applications must be more flexible, thus they are harder to use (planning/design).

Finally, these are a few uses of KBS other than as direct decision support systems for applications.

a) training of personnel on technical procedures

b) assisting in using procedural programs (algorithms)

c) integration of the different modeling procedures (mechanical, electrical, structural,

d) structuring knowledge for feedback or discussion

e) formalizing existing knowledge and identifying gaps in the knowledge as potential areas for research.

Subject 3: Tools for Building KBS Applications

This section focuses on the extent to which existing tools may support the applications described in Subject 2. The tools toimplement KBS were characterized into three groups:

a) General languages (LISP, PROLOG, C, FORTRAN, ...)

b) Representation languages

1) low level (OPS, SRL,...)

2) high level (KEE, ART, PSRL,

c) Reasoning languages (EMYCIN, INSIGHT, Deciding Factor, Personal Consultant,

It was argued that each group handles a well defined set of applications. For example, reasoning languages are well suited for narrow domain problems. Representation languages, on the other hand, are designed for more general systems requiring the use of deep knowledge.

In regard to LISP, it was generally agreed that it has very limited numerical computation capabilities. In addition, since every user defines his own language on top of LISP, it is hard to read for the unfamiliar user. Moreover, team work is discouraged by its cryptic nature. It was also mentioned that PROLOG, although widely used, is less flexible than LISP.

On the other hand, with OPS each user must build his own inference mechanism. Knowledge is represented by 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 to identify possible extensions. These probably would be suitable, in fact desirable, for many 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 costs of this technology drop and the operational familiarity by users grows.

Subject 4: The Art of Building KBS (Knowledge Acquisition)

This section is intended to address the issue of Knowledge Acquisition, either manually (Knowledge Engineering) or automated (Machine learning).

Presently, there is no definitive answer to the problem of having multiple experts contribute to the creation of KBS. It was noted that this problem generally arises with systems built on surface knowledge. Fuzzy set theory and Bayesian logic may help in this regard as well as in selecting the best expert system.

Finally, it. was concluded that research is necessary to identify the appropriate knowledge engineering styles for different types of knowledge (intuitive, case studies, regulations, etc.).

Subject 5: Standards for Testing and Validation of KBS

Due to time limitations, this subject was not discussed in this session. Some insights are included in the panel summary section as well as in the white paper.

Subject 6: Philosophy for Guiding Research on KBS

This discussion attempted to define the impact of KBS on the Construction Industry.

How will KBS impact the way professionals work? What should be the role of universities in developing KBS? Should universities prototype or contribute real world applications? Who is to judge the quality of the worker? What is the role of critical mass (synergistic effect of several researchers working on the same area)? What are the links between Industry and universities? These were all questions that were asked rhetorically and for which the only reliable answers will be found through the experience of the next few years.

2. LARGE GROUP PRESENTATION AUDIENCE RESPONSE

This section summarizes the panel's findings and insights as presented to all Workshop participants. To avoid duplication, only new developments as well as questions and views raised from the floor are presented.

An important question was raised from the floor as to whether KBS are being seen as "black boxes" by the end users. The argument was generally settled by noting that every KBS contains an explanation module. Thus end users can trace the line of reasoning followed to arrive at conclusions, reducing their mystery.

With regard to the “rule induction languages" it was noted that they are essentially decision table processors, which cannot be the only system basis for Construction.

What follows are the views briefly expressed regarding Civil Engineering applications.

- First-time users should start with reasoning tools unless the problem is large enough to justify the use of a representation language.

- Reasoning tools are used mainly for classification problems. A design problem cannot *be* represented in a reasoning tool, e.g., HI-RISE was implemented in PSRL, which is a representation language.
- Should Civil Engineers use representation or reasoning tools? It is suggested that, representation languages be used principally for research purposes. There is no doubt that there is also potential for research with seasoning tools. The idea of bringing the representation tools to a lower level of sophistication and upgrading the level of sophistication of the reasoning tools was strongly pursued. The objective would be the creation of tools that fill the gap between extant reasoning and representation tools.
- Civil Engineers are contributing to the AI field by addressing CE problems that could not have been previously attempted. In the course of which, shortcomings with existing tools are identified and often rectified.
- Civil Engineers should interact with Computer Scientists

Regarding Knowledge Acquisition, four categories of knowledge were identified along with the methods to gather that knowledge. These are presented below in Table 3-2.

KNOWLEDGE CATEGORY	KNOWLEDGE ACQUISITION METHOD
Intuitive knowledge	Direct interview. Expensive and time consuming.
Intuitive but with good precedent	Interviews, knowledge more structured, eg., to bid or not to bid? Faster to prototype.
Case studies	Inductive software or ad hoc logical analysis
Published information	Books, Journals, Flow Charts, Regulations. Not easy or trivial to program a KBS due to the existence of conflicts or contradictions.

Table 3-2 Knowledge Acquisition Methods

Following are the views expressed regarding Knowledge Acquisition.

- If multiple experts are contributing to the development of a KBS and there is conflict about a solution to a problem, generate a series of alternative KBS rather than a consensus KBS. Then use statistical or other techniques to select the best alternative. Behind this suggestion is the assumption that it is possible to evaluate (validate) all expert views.
- If advice is available from multiple experts, then in which order should the knowledge engineer try them?

The following are the views expressed about the philosophy and impact of KBS on the Construction Industry.

- Civil Engineers should definitely influence software development.

- There are applications in which there is no immediate payoff but research still needs to be done.
- Attention should be given to problems having the earliest and highest payoff (not necessarily monetary payoffs).
- Will end-users accept KBS knowing that they are using knowledge that is not theirs?

3. PANEL SUMMARY

Views Expressed:

- Proposals expected to be funded by NSF or others should clearly differentiate Civil Engineering research from Computer Science research. Namely by addressing the civil engineering context of this technology's transfer and adoption.
- The idea of standardization of low end tools (reasoning tools) is not justified due to their short life cycle.
- High end tools (representation tools) are already standardized (PSRL, KEE, ART) and the market is changing quickly to the point where these tools will soon be widely affordable.
- User acceptance (validity and psychological reactions) remains a candidate for further research.
- Continual implementation of classification and diagnosis KBS are still needed to show "proof of concept" and to introduce KBS to practitioners of the Construction Industry.
- Effort and research should be devoted to developing guide-

lines for knowledge acquisition techniques. In Construction most expertise is derived and acquired empirically from various forms of apprenticeship, one of the Industry's unique features.

- AI researchers (psychologists, computer scientists and knowledge engineers themselves) should provide more insights and guidelines for KBS validation and testing. Considerable effort should not be spent in this area by Civil Engineers.

<u>Suggested Research Topics:</u>

<u>Short-term projects</u>: Use lower end tools to solve classification, evaluation, interpretation problems. Among the goals of these research projects the following are just a tentative list:

- to gain user acceptance and developer ability
- to discover techniques for knowledge acquisition
- to identify validation techniques

<u>Intermediate Term</u>:

- Use of qualitative simulation as a means to do risk analysis and evaluate the impact of personnel decisions on the life of the company or even just a project.

<u>Long-term Projects</u>:

- Conceptual and detailed design and planning systems. Emphasis should be on interdisciplinary systems that address costs, constructability, quantities, codes, CAD-graphics.
- Integrated decision support for construction projects. These

systems address costs, schedule, resources, uncertain data, and integrate back to design.

- Guide development of high end tools and look for leading users (NASA, Corps of Engineers, Department of Defense, Department of Energy).

CHAPTER 4

SIMULATION

This panel session considered the models and algorithmic procedures, both mathematical and non-mathematical, that are generally called simulation tools. Of relevant concern were issues of human-machine interaction, integration of site-developed information, and innovative technology data acquisition and processing.

1. PANEL DISCUSSION

The panel leader, Professor B. C. Paulson, Jr., started the session by reminding the participants of several ideas extracted from the white paper.

- There is an urgent need of improved communication of designs (CAD systems, databases, communications)
- Both "classical" (site operations) and corporation (financial, organizational) simulation efforts are important.
- Quantitative methods, data collection and process control were also assigned importance in the contributions for the white papers.
- Since simulation with a computer is a CPU-intensive process, a potential use of supercomputers in this area could foreseen.

After presenting these ideas, the panel leader suggested that each of the participants briefly describe some of their main thoughts and opinions about the topic of simulation. A summary of these contributions follows:

- It is crucial to place more information in the hands of the people that need it, when they need it.
- There is a strong need to develop a lexicon to improve the communication, by unifying the terms used.
- The Construction Industry is quite fragmented. It is therefore important to realize that CAD systems, databases and computer communication tools should contribute toward gluing the parts together.
- Major problems in the Construction Industry are the changes and disputes due to defective design; computer communication tools should also reduce these problems.
- Computers can help the people dealing with the construction task by contributing with graphics to visualize the work; in simple terms, showing "what is put together and how it is put together."
- A typical site operation involves three definite tasks and types of people: the Planners, the Doers and the Controllers.
- The Planners should try to identify with the Doers and work ahead with computers to develop a better and more efficient construction site.
- An important question to ask is if the computers are as useful to the Doers as they are for the Planners. The answer can be given by searching the hierarchy of computer applications at the operational level.

- The main parts of a construction project (laborers, management, equipment, tools, environment) that interact to produce the work can do it more efficiently if the computer is used as the communication tool.
- Merging top-down/bottom-up planning can be accomplished by using the computer.
- The computer has a great potential to produce a more efficient distribution of resources by monitoring the input and the output of construction operations and by helping to analyze the resulting data.
- The rate of failure occurrence in finished projects is much larger than that estimated using probabilistic approaches. The difference is due primarily to design and construction errors. Computer analysis and simulation are efficient instruments to prevent, detect and control errors in a project being designed and constructed.
- Simulation used at the process level: Describes a project in a very detailed form (a system like CYCLONE is an example).
- Simulation used at the project level: Could be helpful to make decisions during the process of construction.
- Simulation used at the corporate level: Useful to bridge the gap between the managers and the tools available. It has been very successful for training decision makers by recreating the working world of the manager.
- With more refinement, tuning and development, simulation at the corporate level can also be used as a forecasting

instrument.

2. LARGE GROUP PRESENTATION AND AUDIENCE RESPONSE

After the presentation of these preliminary ideas by the participants, further discussion was carried on these and related topics, pursuing the following objectives:

- Identifying the main issues
- Analyzing their potential for research
- Finding the relation of these issues with the areas covered by other groups in the Workshop (database and communication, expert systems, robotics).

A summary of the analysis of the main issues is presented in Table 4-1.

Issue #1: Creating and Enhancing Tools--Data Collection and Analysis Techniques

Approach	Description	Linkage
Re	Monitoring and control of input resources to sustain production	Db Ro
Re De	Methodology of construction site simulation	Db Ro
Re De	Broadening and simplifying existing simulation tools	
Re De	Simulation at: Process Level Project Level Corporate Level	
Re De Im	Simulation as operational tool. Problem solving in real time Progress	Ro Es Db

Conventions:

Approach: Re = Research
De = Development
Im = Implementation

Linkage: Es = Expert systems related
Db = Database related
Ro = Robotics related

Table 4-1 Breakdown of the Main Issues and Analysis of Resulting Elements

Issue #2: Human and Organizational Aspects of Modeling and Simulation

Approach	Description	Linkage
Re Im	Staff and tools to support Doers. Cost – Benefit Analysis	
Re Im	Planning/Control/Doing - Define hierarchy of computer needs for Doers	
Im De Re	Simulation at higher level management: - Teach theoretical concepts - Deal with management's qualitative environment - Role playing - Highlight gaps	Es
Re De Im	Simulation as operational tool. Problem solving in real time progress.	Es
De	Define relationships Field people --- Computers	Es
De	Need of human interface/computers	
Im	Simulation to support strategical decision making	Es

Conventions:

Approach: Be = Research
De = Development
Im = Implementation

Linkage: Es = Expert systems related
Db = Database related
Ro = Robotics related

Table 4-1 Continued

Issue #3: Interface among tools and applications

Approach	Description	Linkage
Re	Design and Construction error detection, control and analysis	Es
Re De Im	Merging top/bottom and bottom/top planning Interface between boundaries of tools	
De Im	Fragmentation of Industry Database interface	Db
Im	Information to the right people at the right time	Db

Conventions:

Approach: Re = Research
De = Development
Im = Implementation

Linkage: Es = Expert systems related
Db = Database related
Ro = Robotics related

Table 4-1 Continued

Subject 1: <u>Creating and Enhancing Data Collection Tools and Analysis Technologies</u>

Several specific elements that give more detail to this issue were discussed:

- Monitoring and Control of Input Resources to Sustain Production. This is an area that requires further research, and involves the capture of the data on input resources, its analysis using simulation, and a feedback loop to the system to make it more efficient. This area is related to research in databases and communications as well as robotics.
- Methodology of Construction Site Simulation. The ideas of new advancements in the simulation models and new modeling techniques themselves were implicit in this discussion. Further research is required and some refinement of the existing methodologies is also necessary. This area is definitely linked to research in databases and robotics.
- Broadening and Simplifying Existing Simulation Tools. Research is required to find new simulation tools and enhanced applications. Development is required to produce user-friendly applications, by utilizing graphics, image recognition and speech synthesis software.

Subject 2: <u>Human and Organizational Aspects of Modeling and Simulation</u>

The detailed aspects of this issue that .were discussed are summarized:

- Staff and Tools to Support Doers/Cost Benefit Analysis.

  One of the major problems of the Construction Industry in the U.S. is the lack of supportive staff ("low overhead crisis"). A comparison was given with the Japanese Construction Industry where more supporting staff as well as more elastic work rules help the Doers to generate more efficient work. More research in simulation tools as well as implementation of recent developments are required to analyze and help to give a solution to this problem.

- Planners/Controllers/Doers. Define Hierarchy of Computer Needs for Doers. One question raised is that the Doers are so involved in their day-to-day tasks and problems that it is important to find a way to make the computer helpful and instinctive for them.

  Comment: a question was raised about how realistic is the concern of computers being "overused" by Doers.

- Simulation at Higher Level Management. Teach theoretical concepts, deal with management's qualitative environment, role playing, highlight gaps. It was agreed that this area is principal: successful applications (e.g., AROUSAL) have been developed for managerial training, and with some research and implementation of existing tools, the potential for forecasting is promising. It is believed that a close relation with research in Expert Systems would be very profitable.

  Comment #1: Tools in behavioral sciences have already been developed and therefore can be implemented in simulation models. An example can be given from AROUSAL, where personnel motivation is successfully modeled.

Comment #2: AROUSAL is an example of a simulation tool applied at organizational (or corporate) level. CYCLONE is, on the other hand, an example of a simulation tool applied at operational level. An important challenge is to try to integrate the different levels of simulation.

- Simulation as an Operational Tool. Problem Solving in Real Time Progress: Research, development and implementation of simulation tools are necessary, to produce instruments for problem solving in real time. This topic is considered related to developments in Expert Systems.
- Define Relationship Field People/Computers – Need of Human Interface and Computers: The trend should be to produce systems closer to the user. The tools to be developed are graphics. image recognition, speech synthesis, applied to simulation software.

  Comment: It is time to think about the changes that Expert Systems and Simulation are beginning to produce in the workers environment, with several types of implications.
- Simulation to Support Strategical Decision Making: Simulation is definitely an excellent tool for training purposes. (In many areas, the "role playing" emphasis of simulation has been used very successfully). With proper implementation, simulation can be used as a forecasting instrument.

Subject 3: Interface Among Tools and Applications

The discussion of this issue involved the following areas:

- Design and Construction Error Detection, Control and Analysis: Research is needed to develop efficient mechanisms to avoid, to control or to learn from errors at the design and construction stages. Research in Expert Systems is closely related to this area.
- Merging Top-Bottom and Bottom-Top Planning – Interface Between Boundaries of Tools: The integration of all the planning tools is important from the corporate level to the operational level and vice versa. Additionally, a universal lexicon is necessary to improve communication at any level.
- Fragmentation of Industry/Database Interface: The problems of communication caused by the fragmentation of the Construction Industry can be alleviated with the use of computers via development and implementation of database interfaces and CAD systems.
- Information to the Right People at the Right Time: Implementation of the convenient tools is required to perform this task. These tools are basically databases and computer communication hardware and software.

Subject 4: Comments at the End of the Presentation

After the large group presentation, several comments were made by the audience. Those most crucial were:

- Simulation should also be used as an experimental tool to evaluate theory.
- An example was mentioned of a discrete event simulation system, linked to an Expert System whose rules govern the simulation system. This system was said to be developed using KEE (a proprietary software product).
- Supercomputers, with their capability of extensive parallel processing, constitute a polemic topic with regard to their potential for research in the next five years. Some participants were of the opinion that their potential should be considered, while some others think that their limitations (mainly, input/output and disk paging) are an obstacle for research in Construction in the near future.
- It was recalled that simulation provides credible and realistic answers if properly used, but that it does not guarantee optimality of results.
- A participant asked why emphasis was not given to the numerical problems and probabilistic concepts implied by simulation, and especially to the estimation of the variability involved. The answer was that although it is an important topic, other aspects believed to be more important were discussed. Additionally, some characteristics make the

simulation in Construction very unique. Large variances are involved, as well as high degrees of correlation between parameters, all of them very difficult to estimate.

3. PANEL SUMMARY

The different presentations generated new ideas as well as a sharper vision of some of the issues discussed previously. A summary of this discussion is captured by these comments:

- Simulation is a necessary tool in robotics. Research in these two areas must be well interrelated, since simulation will be useful at the development, testing and operational stages of robots in Construction.
- Simulation is a strategic tool for managers. The success of a system like AROUSAL as a realistic training tool, confirms that simulation as a worthy forecasting tool for construction managers.
- Simulation is a potential instrument for Expert Systems. The concept of a "demon" used in AI terminology is suitable for a simulation process invoked from an Expert System to infer information, when not enough data is available.
- Simulation has great potential as a sensitivity analysis tool. The impact of changes in construction operations can be assessed with properly tuned simulation. If this is accomplished in real time, simulation becomes an operational tool.

To try to infer what the expectations of the participants were about further developments in simulation, an exercise of thinking in a typical construction operation (reinforced concrete) was discussed. How would simulation be useful?

- In analyzing the implications of new construction materials.
- In selecting the appropriate tools, equipment, and construction procedures.
- In assessing the impact of the environment.

This leads to the important need of integration of simulation tools. The research efforts should tend to link all the elements of the Construction process together, from the general point of view of top management down to the operational details.

In an ideal world this can be conceived as a "war room" where the team of experts can have all the tools to simulate the projects and take appropriate decisions. It is important to notice that this would be linked to Expert Systems, Robotics, Databases and Communications and additionally, would require all sorts of external data (economic indexes, labor quality and availability, weather, etc.) that we presently ignore.

A final comment was made on the integration of simulation and other tools. The question is, what would be the ”dominant structure" of' this integrated system? It is interesting to remember that originally CYCLONE was governed by a scheduling (CPM) program that involved simulation processes when needing durations for the activities. In the future, the possibilities for this dominant structure are widening: CPM, organizational analysis programs, Expert Systems, etc.

Chapter 5

ROBOTICS

The intent of this Workshop panel was to define the basic research issues surrounding robotic applications to Construction. Scope included specific applications; basic technological issues such as sensors, mobility, control, large forces, and system integration; and ancillary issues including but not limited to safety, industry acceptance, socio-economic concerns and "design for constructability."

1. PANEL DISCUSSIONS

The session was opened by panel leader Daniel Rehak, who asked each of the participants to introduce themselves and their current research interests in construction robotics.

Contents discussed during the opening panel session can be divided into three parts and this chapter is organized in that manner. To minimize redundancy, some of the items brought up in the panel session are covered in the following section on the large group session.

The initial step was to identify who is doing what. Simply stated, the following formal efforts were noted:

A. Carnegie Mellon University

- Organized its Robotics Institute approximately three years ago, with a collection of personnel representing more than just a Civil Engineering background. Prior developments by mechanical and electrical engineers have been enhanced to cope with the civil engineering problem domain. Industrial donor support has been significant.

- Production of a tethered robot for the cleanup at Three Mile Island Power Plant.
- On-going involvement in many other projects, including mining and hostile environment settings.

B. Caterpillar Tractor Company

- Broad ranged studies:
  - Unmanned factory material handlers
  - Operator aids, including machine vision.
  - Fleet management and mining equipment flow.
  - Online payload monitor.
  - Diagnostics. including "opportunistic repair."

C. Technion University of Israel

- Potential applications to building construction:
  - Development of general strategy, including identification of work tasks most amenable to robotic applications.
  - Development of a basic configuration of robotic-worker teams and work styles.
  - Designing for constructability by robots.

D. Massachusetts Institute of Technology

- Broad range approach (non combat role)
  - Robots to assist in erection of rapid mobilization shelters and structures.
  - Inspection of labor intensive operations.

E. Georgia Institute of Technology

- Economic feasibility study of work tasks adaptable to robots.

At this point, the question was raised as to what differentiates a robot from an intelligent machine or an automated factory process. The critical attributes of a robot were generally agreed to be mobility, autonomy, the capacity to deal with large forces, and the (cognitive) ability to cope with dynamic, unstructured, harsh environments. Moreover, they rely upon a sensing-control feedback loop, and process information from a project database in a rule based fashion. In general, the participants agreed that they could recognize a robot on sight, but could not describe one very well, especially in contrast to the current generation of intelligent machines; e.g., laser-guided road pavers and undersea pipelayers.

With this review in mind, the panel then turned to an examination of why robots would find a place in construction. The consensus is that, in order of priority, motivation will stem from: (1) increased productivity and more attractive economics; (2) improved worksite safety because robots will be assigned the more hazardous tasks; (3) additional brute strength; and (4) enhanced construction quality. In fact, the C-MU experience has been that the importance of benefits is re ordered for most construction projects as follows: (1) safety; (2) quality control; (3) superhuman tasks; and (4) productivity. For highrise building construction experience in Israel, Professor Warszawski suggested an order of (1) productivity; (2) superhuman tasks; (3) quality; and (4) safety.

The particular order of priority was felt by this panel to be an important issue by itself because it gives direction to designers of both robotic hardware and software systems.

The brief amount of time remaining was dedicated to a review of a five year plan for robotics research as developed by the Carnegie Mellon University team. That schema is presented in the following section.

2. LARGE GROUP PRESENTATION AND AUDIENCE RESPONSE

Professor Dan Rehak began the presentation with a definition of construction robotics. Emphasis was placed upon the differences between robotics in Construction and those in Manufacturing. Construction robotics must deal with:

- mobility
- large forces
- unstructured environment
- open/harsh environment

Many of the traditional robots developed in mechanical and electrical engineering laboratories would have difficulty navigating across simple topography, tripping on electrical cords and bouncing off walls. Construction robots must be able to overcome these and more difficult obstacles.

Mr. Gene Leach of Cater pillar Tractor addressed the topic of Industry's role in Construction robotics research and development. Caterpillar's current involvement includes development of an unmanned material handler and operator aids to increase equipment performance. Leach emphasized the feasibility and value constraints within which

Caterpillar must comply. He mentioned the possibility of providing assistance in equipment and training. The importance of the economic marketplace and investment return for all Industrial participants were stressed in this discussion.

The issue of cooperation among the various parties involved in Construction robotics can be summarized by five different levels. They include:

University-University:	The sharing and division of work among academic teams.
University Industry:	Includes both equipment manufacturers and construction contractors.
University-Government:	Government agencies such as N.R.C., D.O.T., D.O.D. and Army Corps of Engineers.
U.S.-Foreign:	International involvement with the Japanese, Europeans, etc.
Interdisciplinary Teams:	Technical held from computer scientists, mechanical and electrical engineers. Contextual work to be done by civil engineers.

Dr. L. R. Shaffer, representing the Army Corps of Engineers' Construction Engineering Research Laboratory (CERL), discussed the military's interest in Construction robotics. He referred to a project currently underway at CERL, which uses robotics to assist in the rapid construction of numerous wood framed buildings during a mobilization. Dr. Shaffer also mentioned another military application, specifically a tank ammunition handler. Funding for this project was on the order of 10 million dollars.

The pressing research issues needing academic attention were then grouped by the panel leader into four categories:

Concepts/Feasibilities: Includes such issues as cost effectiveness, improved productivity, higher quality control, and technological feasibilities.

Basic technologies: Determine the special needs of Construction and examine the various options. Problem areas include sensors and interpretation, manipulators and effectors, compliance, environmental impacts, mobility, and control.

Demonstrations: Industry is a hard sell, and without working demonstrations, their support will be limited. Demonstrations must be limited in scope to handle very special, unskilled tasks.

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 similar vein, should begin at the lowest level, with increased sophistication coming with experience.

Beyond these direct, technological concerns looms the issue of institutional change, a sentiment expressed strongly by many of the Industry representatives in attendance. That is, many aspects of robotic-based Construction will differ from conventional construction technology. The problem is how and where the changes occur. Is therea need to fundamentally rethink the whole design/construction process?

Immediate economic constraints tend to force the view to a more micro-level, one in which we individually tailor components, such as the construction site, materials, and equipment, to suit robotics. However, the macro-level still needs to be investigated; Professor Warszawski mentioned its importance and the work he is doing at the Technion University of Israel.

There are sociological issues to deal with regarding design for constructability. What degree of conformity in products 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 accept this responsibility? Does this work force become supervisory or employee?

Current research in the area of design for constructability not only includes Warszawski's work, but extensive work done by the Japanese. This includes detailed task analysis, computerized process definition, and development of a set of fundamental activity tasks.

Having made the argument that Construction Robotics research was only about five years old, Professor Dwight Sangrey proceeded to set forth an agenda of research needs for the next five to ten years. He wisely structured it on a three tier basis (Table 5"1). Presentation of this agenda spurred several comments, most of a "why not this idea" nature. The common response was that any proposal at the Tier III level should be judged by the same criteria currently used by funding agencies: relevance, technical competence, long"term goals, likelihood of success, etc. An issue of a more fundamental nature was how to organize, manage and reward a team of researchers from different functional backgrounds. Sangrey used the C-MU Robotics Institute as an answer: namely, for large projects, establish a Center where the personnel can concentrate on the multi disciplinary project. Put as much of the promotion and incentive system in that Center as the University will allow, then manage and act in a fashion that under scores the sought after cooperative spirit. In concluding, Sangrey stressed persuasively that such cross-disciplinary projects will become more commonplace is the future, and researcher s need to prepare accordingly.

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.

Table 5-1 Construction Robotics Research Agenda

3. Panel Summary

The consensus in the summary session was a feeling of accomplishment. Elements of motivation, research issues, and a five-year plan had all been established. Interactions and overlap between Robotics and the other three panel groups of this Workshop were recognized and noted. Carnegie-Mellon's dominance in the field of Construction Robotics provided the central leadership necessary for the above results.

In the panel summary session, three additional points were reiterated. The first is the establishment of a vehicle for the interaction and cooperation among the various entities involved in construction robotics. Carnegie-Mellon's Robotics Institute seems to be ideally suited for this function. Rehak suggested three ways to promote cooperation:

- To set aside one hour for discussion for the purpose of developing further cooperation to be held at the June 1985 Workshop in Construction Robotics at C-MU.
- A more equitable division of labor between research institutions so as to avoid repetition and inefficiencies.
- The possibility of publishing a periodic Construction Robotics newsletter.

A second point of action would be the establishment of a library or bibliography of' papers and publications relevant to Construction Robotics. The panel leader made the analogy of such a bibliography to one currently available on the topic of expert systems at C-MU. A nationwide or international bibliography on Construction Robotics would benefit all interested parties.

The final point of agreement was that of change. Construction Robotics, in its embryonic state, will continue to evolve. It is difficult to even anticipate what may happen within the decade. In large part, the maturation of Robotics will proceed at the rate governed by developments in the three other Workshop areas and some yet to be discovered and developed.

Chapter 6

SUMMARY AND CONCLUSIONS

This chapter represents a meta-summary of the most significant points that evolved from this Workshop. It is neither a substitute for nor a repetition of the individual subject chapters (2"5) or the White papers (Appendix A). Still, some comments of an overview nature are appropriate, especially as the four topic areas relate to each other.

Project-Wide Databases and Communication

In the minds of most participants, this panel was the underlying, unifying topic of the whole Workshop. The idea of being able to take advantage of existing electronic communication technology is eminently attractive for several reasons, one obviously being the ability to integrate the design and construction functions more closely than ever before. The promise is an actual one since other segments of the national economy have been able to recognize and effect such cross" communications; eg., banks, airlines, computer graphics vendors.

A key issue in this topic area eventually will be identification and development of extremely flexible and efficient database architectures that will allow the project elements and their attributes to be stored in an entity-relational fashion while still being accessed with high rates of input/output speed. Consider, for instance, a simple steel beam. The designer is principally concerned about structural, mechanical (fire rating), corrosion and perhaps aesthetic properties.

A detailer/fabricator is interested in weight, tolerance, and commercial availability factors. Various contractors may be concerned about the ability to fasten attachments (pipe hangers), surface area (painting and fire protection), and configuration as it relates to other neighboring building components (constructability). Other related issues will include testing and inspection, lines of sight, point of origin (domestic vs foreign manufacture), space planning, etc. When the focus is shifted from the relatively simple case of an individual structural member to an operating system (boiler) or functional space (clean laboratory), the networked memory requirements explode dramatically.

Computers with unprecedented input/output speed, as opposed to sheer computational power, will be vital, and will come to the user's desktop sooner than we expect. In actuality, the greater obstacle to such online telecommunicating is on the software side of the equation. New, hyper-efficient database architectures mst and are being conceived by computer scientists today. It is the responsibility of this profession to choose and adapt the right schemes for the Industry's needs.

There is another impediment to the goal of integrating design construct information on one master database, and it is not technical so much as institutional. Namely who is to take the first step to support financially, organizationally, and information-wise such a mammoth undertaking. The answer probably lies with big project owners who construct a large number of similar types of projects. Examples would include the U.S. Military, very large hotel and restaurant chains, and electric and gas pipeline utilities. As a point of information, the Electric Power Research Institute currently is conducting research with Duke Power Company for the purpose of developing guidelines for CAE/CAD database integration[3].

Knowledge Based Systems

Validation of the entire family of computerized knowledge systems (KBS, KBES, ES) is an important concern to all affiliated with this technology. The expert systems developed as pioneer efforts in construction must be the very best efforts possible. If Industry acceptance is to be achieved, it will be earned by researchers who take pains to validate even the prototype systems. This point is crucial, not just for the field itself but for the other three areas evaluated during this Workshop as well. For example, a robot will likely use some form of an expert system to evaluate obstacles in its path and strategies for maneuverability; e.g., skirt the object, move it, or demolish it. The database panel saw expert system technology as a way to trigger automatically the release of information to the correct project personnel, etc. Yet the feeling was expressed that this concept could be "oversold," and any good research would be lost in a sea of lowerquality issues.

A related matter was how to promote acceptance on the part of the Construction Industry. Part of the key to that challenge was provided by the panel when it decided at the outset to concern itself with "Knowledge based Systems" and not "Knowledge-based Expert Systems." In

[3] Electric Power Research Institute, Guidelines for Applying Computer Aided Engineering Systems to Generating Power Plants. EPRI Research Project RP 2514-3, Nov. 1984.

other words, de"mystify the subject somewhat.

Another point raised that may prove to be crucial was that of the role of the knowledge engineer. The first generation of these systems will require some company-specific tailoring and personnel training for them to be accepted. (As a parallel, computerized network scheduling was slow in being accepted by contractors, even though the benefits to be reaped were principally theirs.) Thus the performance of a knowledge engineer with a firm understanding of' the "construction context," perhaps acting in a consulting position at first, will likely determine how readily these tools are accepted as well as how useful they eventually prove to be.

As with any new, untested technology, the criteria for evaluating these types of research proposals and applications will include demonstrated capability by the Principal Investigator; focused, important scope; relevance to Industry needs; and pertinence to an important long term research program.

In terms of promise of specific research, this writer is personally convinced that diagnostic-forecasting products have the highest priority. So many of the Industry's problems stem from the disparity between individuals and even entire companies to plan with acceptable degrees of accuracy, whether forecasting specific project cost or schedule performance, or at the higher level of company strategic planning. The use of such proven systems should go a long way to upgrading the entire Industry's professional competence.

Simulation

The simulation panel started discussions with the significant advantage of being a mature field with a group of researchers that have been collaborating for years on time-tested tools. A unique event for this group was exposure to a realistic simulation model of the corporate operations of the firm. With the exception of some limited efforts in the mid 1960's, notably Carnegie-Mellon University's Building and Excavation games and Professor Bjornsson's BIG (a bidding and managing model), most of the research has been concentrated on the analysis and design of construction site operations. The demonstration of' Professor Lansley's AROUSAL package revealed new vistas of management simulation research and development.

Graphics and other data reduction, interpretation, and presentation tools were stressed because the human-machine interface was perceived to be as important of an issue as ever. Though the panel did not spend much time discussing parallel processor architectures for computers, like those common to the latest generation of supercomputers, this research field appears to be poised to model operations at a much deeper level than ever before with simultaneous simulation concepts. In such cases, the collapse of massive amounts of data into simple, intelligible forms will be essential.

Professor Paulson led an energetic and futuristic discussion of a "war room” scenario in which major project participants cloister themselves as a planning procedure to large project kick off. Supplementing this sequestered group would be access by these individuals to specific simulation tools and expert system packages, with the appropriate level of security and detail, to plan intelligently the project.

As a final note, the table presented in Chapter 4, is a very useful picture of the panel's recommendations.

Robotics

Three salient points emerged from the Robotics panel discussions. First, Carnegie-Mellon University is well ahead of other research teams in this country in terms of development effort. Second, efforts at other institutions are being encouraged to breed more peer review and collaborative interchange with the C-MU team. Thirdly, adaptation of the first generation of robots as developed by computer scientists and mechanical and electrical engineers to real construction tasks will be a gargantuan endeavor.

As Professor Rehak cited, Construction Robotics must deal with large forces, changing topographies and environments, hazardous conditions, and autonomy requirements not encountered in the stationary point, manufacturing environment. A lesson to be learned from the C-MU experience is that it is indeed possible to bring individuals from different disciplines together in a university setting to work on real world problems like this. Moreover, it is imperative that this be done to conquer the contextual complexities of these types of problems.

The large group discussions revealed that Robotics are of major concern to many private sector companies and especially so for the military. The expected concerns of mobility, serving, control, and real-time interaction with a project database were explored in considerable detail. Also, issues and on-going efforts such as Robotic safety and feasibility were examined.

Some of the most provocative discussions of the whole conference stemmed from a review of the work by Professor Warszawski and others at the Technion regarding the impact of Robotics on building products and methods. Since a robot can feasibly handle and set a building block five or ten times the size of' an existing unit, why not produce them in the larger sizes so less unit handling is required? The institutional ramifications are certainly dramatic and perhaps largely unanticipatable.

The table presented in Chapter 5 represents a clear pattern of the recommended research directions for the next several years. The challenge of this field will be for other research units to develop the critical mass necessary to spur and provide a sounding board to the efforts of C-MU.

Interdependence

At the Workshop's outset, the participants were charged not only with developing fertile ideas for new research directions in their respective panel areas, but also from a perspective of interdependence between the four areas. The actual division of the Workshop theme into these four target areas was more for convenience of discussion than for any other reason. As has been indicated above, these boundaries were often exceeded and reliance on parallel developments in the other three areas clearly expressed by the panel leaders.

Many of the participants expressed the opinion that the database group was the unifier of all four. It is certainly easy to see the interrelationship between the topic areas when viewed from that 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 remaining (as stored in a project database). Any planning exercises involving simulation tools would necessarily rely on an efficient, comprehensive data set. As discussed before, so would intelligent, autonomous Robotic systems.

The interaction is two-way, though. Clearly the types of efficient data storage schemes envisioned here will need a machine order intelligence (expert system) to remedy the bane of large databases: execution slowdown resulting from inefficient data structures. Similarly, the sensing units of robots will provide real-time environmental and performance information to a simulation module to allow the robot to "learn" better work methods.

The key to getting these four interrelated research programs to work together would appear to be major, multi-task research endeavors like a space station project. Though it seems counter to prevailing political philosophies, some federated endeavor with sponsorship beyond the 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 this 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 Dr. Paul Teicholz.

That vision is presented in Table 6-1 as a time-scaled plan of execution. Naturally the immediate research efforts should be small scale individual undertakings. with initial dedication to the most promising projects as identified throughout this report. Inspection of this table reveals, not surprisingly, that as we move further along in time, this research will eventually come together in the fashion described earlier. The challenge to us, the researchers, will be to exploit the synergistic potential available from uniting these separate puzzle pieces.

RESEARCH TOPIC	TIMEFRAME		
	SHORT TERM	**INTERMEDIATE TERM**	**LONG TERM**
1. Project-wide Databases	Extract Quantity Data from CAD database	Replace plans and spec's as design end product; make them by products	Add knowledge components to database to facilitate communications flow, etc.
2. Expert Systems (Knowledge based systems)	Simple diagnostic system; stand-alone; structured	multiple objective; context de pendent; middle management problems; integration with database	Built into control systems; part of design process; adaptive
3. Simulation and Modeling	Ease of use; graphic input and output; "What if" capability	Integration with planning and control systems, and project database	Integration with Robotics
4. Robotics	Identify pay off areas; solve repetitive problems	Modify Construction practices where desirable; introduce in less constrained problem domains	Integrate with project database, KBS to allow greater automation

Table 6 1 Long-term Strategic Plan for Computerized Construction Research

SUMMARY

Looking back at the discussions and issues themselves that were raised at this Workshop, several points seem to stand out as being crucial for the continued growth and maturation of the construction research community.

First, this community must improve its contacts both within itself and with Industry and government. Periods of software demonstration were eagerly attended reflecting the thirst of learning what others were doing. It was pointed out once again that Industry's focus is much more near-term than a university researcher's, and without communication the paths of the two will undoubtedly diverge. Workshops with invitations to Industry leaders, ASCE Technical Sessions with focus on research and technology transfer, and industrial affiliates programs at the universities are good examples of how this contact can be nurtured.

At the same time communications within the circle of construction researchers has to be developed more fully. Sharing master's degree level research, proposal writing and review tactics, and expertise in selected areas of research endeavor, among other things, can be accomplished within the existing cooperative framework. This will prove especially important over the next several years as the anticipated reduction in government supported research becomes reality.

With that weaning of government support, Construction researchers will have to "bootleg" and work closer with Industry to get the research done. That also will mean listening and observing more carefully what the needs of the Industry are. Eventually the time will come and be recognized that operating as independent, balkanized research units is inefficient, especially in the face of diminishing resources.

The attendant pain of such resource shrinking would be mitigated by an effective Construction Research Consortium. This low-key, informal unit would facilitate communication between the member universities and Construction research consumers (government agencies, private companies, economic planning teams) as well as the schools themselves; work with potential clients and funding agencies to identify important problems and the best researchers; and promote the validity of construction engineering research. Various mechanisms to establish such a framework should be explored in the future.

Finally, the need for maintaining and even improving the quality of our research was impressed upon the Workshop participants. To move forward in gaining the respect of our colleagues in other engineering programs and of the Construction Industry itself, it is imperative that quality of research continue to be enhanced. This is manifested by research proposals, technical publications, conferences, and student instruction and training. Most University Construction programs have enjoyed the privilege of being subjected to less of the "publish or perish" pressure than many other disciplines. Since all the resources necessary for high quality research are currently plentiful with the possible exception of large numbers of Ph.D. candidates, this research community has no excuse for not getting the job done. Particularly with the excellent recommendations for future research contained in these proceedings.

APPENDIX A

WHITE PAPERS

Group 1

COMPUTER APPLICATIONS TO PROJECT COMMUNICATIONS,

DESIGN, PLANNING, CONSTRUCTION AND CONTROL

Drafted with input from

Lance Bell
Chris Hendrickson
Bob Logcher
John Melin
James Neil
Ken Reinschmidt
Allen Russell
Paul Teicholz

By

Keith Crandall and Le Boyer

INTRODUCTION

This area is a broad arena of possible research with communication of ideas, plans and progress a central theme of this work group. In essence, computer applications in this area should be directed to foster better integration of activities, to provide aids for decision making, and to enhance productivity. This direction must be based on a clear understanding of the constituent parts of design, construction, and facility management; as well as the discipline and standardization associated with successful computer applications. Certainly the widespread fragmentation of planning, design (of both final facilities and the construction assembly process), construction and operation provides some significant opportunities for improvement.

With the ready availability of small and inexpensive but very powerful computers, numerous major changes have occurred in computer use in construction. New powerful and utilitarian software is sprouting up daily. Computer use in the field offices is expanding rapidly. Users are developing and tailoring personal software for their work (with the sole criteria that they perform a useful function within the organization--there are no industry standards being considered or applied). While this new environment is removing many common applications problems from the research agenda, it is requiring that the profession be prepared to deal with and be able to handle a whole new set of more involved problems. Many of these problems are the direct result of this explosion of hardware and software development under an ad hoc environment. We are truly "constructing" a Tower of Babel, where these very successful individual applications are not only unable to talk to each other but appear almost by design to prevent required communication.

Expressed explicitly or implicitly by the contributors to this area is that the key issue in computerized project communications is the existence of integrated data bases. The integrated data base(s) should include life cycle data bases for individual projects and knowledge bases related to the general elements of projects. A life cycle data base would include not only the description of what is to be built in the form of digital and descriptive information but the proposed and actual chronology of design and construction including the computerized analog to "as built" drawings. The knowledge bases related to general elements might include standardized planning sub-networks, resource requirements (labor, materials and equipment), communication information, and indication of interrelations with other elements and impacts on members of the project delivery team.

All parties to the design and construction would have access to and communicate through this database systems. The database system is not only central to this topic area but closely tied to the other four major subject areas of this workshop. This database system is related to knowledge-based expert systems as it should acquire the history of previous projects as knowledge to be used to generate information flow and possible design information for the new projects, their estimates, schedules, etc. The relationship to computer applications to analysis and design of site operations evolves in that the system should be able to show the progression of the project and location of the workers, equipment, and materials on the project as one might simulate the construction. The project database should allow organizing and structuring of the data to facilitate information exchange during design and construction, for various functions within a company (estimating, scheduling, control, etc.) and between companies (billing, progress payments, shop drawings, etc.). The relationship with the robotic applications subject area evolves in that the digital model of the project is the knowledge for robots informing them of what they must do and communicating the constraints of the environment in which they must operate.

This paper outlines several sub-topics which allow key communication issues to be viewed in terms of the necessary integration of design, construction, computer science, and other traditional disciplines. These sub-topics include: Industry Wide Standardization, Database and Integrated Systems, Planning and Control, and Communications. The sub-topics provide a convenient, although not mutually exclusive, grouping of the research areas suggested by the potential participants of this work group. These were selected and ordered since research advances in each sub-topic area will enhance additional development in the subsequent sub-topics. The related research proposals received from the participants are grouped under these topic areas. A brief introduction of the significance of the topic is presented prior to this listing (some research concerns were included as part of the introductions).

INDUSTRY WIDE STANDARDIZATION

One attribute of formalized computer application development is the requirement for rigid definition of terms, analytical processes and the handling of exceptions. The successful applications to date are a result of this standardization within the individual disciplines that comprise the construction industry. Designers have their codes, their standard fabrication and material specifications; professional organizations have developed standard contract administration specifications; construction planners have adopted several standard scheduling tasks, but none of these groups have attempted to work with all the others to develop a unified set of standard terms and definitions to ease communication. The need for standardization is especially significant in the computer application environment as programs are unable to apply judgment in the same manner as a professional working with a manual system.

Much research has been done in Europe and work at the Bureau of Standards has been encouraging. These are recommended characteristics for these proposed standards:

- Several summary levels from the lowest level of detail to the project level.
- Must be able to accommodate the various Work Breakdown structures (system, work element, etc.)
- Provide a linkage between design elements, their construction

designation, required quality assurance, and construction tracking.

- Provide error reduction by creating standard terminology between the various disciplines.

The proposed research includes:

1. Standards Development
   a) Life cycle databases and information flow represents a fruitful research area. Engineering and Construction databases are typically restricted to one project domain such as structural analysis or construction cost accounting. Communication is typically difficult or impossible. This fragmentation is costly and error prone as information is transcribed (e.g., by manual takeoffs) or unavailable. Relevant tradeoffs between design and finance, between initial and maintenance costs, between construction cost and time, and other factors are often obscured. Treatments of such tradeoffs are typically approached in an isolated, case by ease fashion. Relevant research in the area would include database design and information transfer standards.
   b) Communications standards are necessary so that the three-dimensional design model, along with nongraphical attributes, can be communicated among all project participants regardless of the specific computer equipment used.
   c) There is a need to standardize ways in which project information can be effectively communicated between owner, designer, and construction contractor. For example, industry-wide coding procedures and specifications for piping, electrical and instrumentation materials would facilitate the transfer of bill of materials files between the designer and construction contractor. Employing standard coding procedures in Computer Aided Design (CAD) algorithms would eliminate the current practice of writing interface computer programs to transfer the files.

d) Investigate the effectiveness of standardization developed in Europe including the SFB classification system. Determine which characteristics would be meaningful in developing an industry-wide classification system based on existing U.S. design, CSI, and other relevant standards.

DATABASE AND INTEGRATED SYSTEMS

Database technology is the basis of Integrated Systems. There is an urgent need to truly integrate the design, contract specification, contract field planning and control, and facility management, functions. This integration relies upon developments in prior topic areas for final success but topic area development will continue in parallel.

The research issues under this topic are divided into Design/Construction Integration, Field Data Integration, and Database Concerns.

There are many users of data that currently reside in drawings, e.g., estimators for the various trades or functional areas, purchasing department, planners, cost control personnel, etc. After a structure is completed, the as-built drawings are used to give the owner the information needed to maintain and modify the structure. Research is needed that will allow the information currently defined by plans, drawings and specifications to be captured when it is defined in a computer database. This is already taking place for quantity takeoff data embedded as text data in a CAD database. The project database should provide the means for incorporation of all design changes into a single design model, A permanent audit trail of design changes and authorizations must be provided in the database (optical storage devices may provide the ideal medium for this). Research is needed in improved data structures to facilitate the management of changes. For any given design parameter, it should be possible to look downstream in the design/construction process to identify all the conditions that a change in that parameter would affect, and to look upstream in the process to find all the conditions that, if changed, would affect that parameter. The feasibility of instantaneous communications through the database implies that any proposed changes must be identified to all affected parties before the change is permanently implemented, or it must be possible to retract the change if necessary. New methods for authorizing changes are needed. (Perhaps some electronic polling function?)

Integrated project control encompasses planning, control and data recovery. It can be compared to a chain whose strength is only as great as its weakest link. We now have very sophisticated project control computer systems which have been designed by some of the brightest minds in the world and are normally operated by professional, degreed personnel. Yet, the success of these systems is total dependent upon such things as the quality of raw data provided by a foreman who may have minimal communication skills and no understanding of the significance of what he/she is reporting. Or, we may be preparing estimates based on data derived under conditions totally unknown to us. The point is, all functions within a total system must operate at a confidence level high enough to give credibility to the total system.

The following are among those considered weak links in the chain:

1. Validity of databases.
2. Understanding of the effect of varying conditions on labor productivity.
3. Accurate conversion of design documents into work quantities.
4. Evaluation of the combined effect of construction variables (productivity, weather, deliveries, risk factors, etc.) in estimating and scheduling.
5. Accuracy of first-level reporting.
6. Evaluation of the total impact of changes.
7. Transfer of project experience data to the planning database.

With more distributed data processing within construction organizations, we see a trend towards less sharing and coordination of data and more towards personalized and individual data. For long term success of distributed processing, methods and strategies are needed for dealing with a combination of personal and shared data. This must include data extraction, polling strategies and auditing capabilities.

Proposed Research in this Topic Includes:

1) Design/Construction Integration
   a) Define an approach to capture the relevant data during the design process.
   b) Define how the data can be extracted for subsequent database required for downstream systems, e.g., how can relational database capabilities be used to link the various database requirements.
   c) The capture and downstream use of data will significantly alter current design and construction methodology. It may also alter the current organization of the industry since it will tend to favor companies where there is a greater degree of vertical integration. These nontechnical issues will become clearer as this capability grows. Perhaps these issues (legal, competitive, organizational) should be given some thought now.
   d) Define data structures to facilitate the management of changes.
   e) Research into the impact of design changes on all contractual parties to a project.
   f) Alternative methods for authorizing design changes.
   g) Methods for interrelating computer aided design with estimating.
2) Database Concerns
   a) Define database requirements for each functional area, e.g., building--electrical, mechanical, framing, foundations, etc.

b) Data abstraction techniques for construction site data.
c) Representation of organizational roles and responsibilities for construction industry organizations.
d) Knowledge based inquiry mechanisms for database extraction.
e) Inferencing on performance from responsibility representations and performance data.

PLANNING AND CONTROL

Project planning and control has been a natural area for computer application. Excellent computer systems are available for handling project controls. The better ones have a scheduling module plus a database management capability which provides all the flexibility needed to format and interrelate the datasets needed for total control. The weaknesses are in the validity of both planning and actual data. There are many computerized estimating systems available, but these are no more accurate than the quantity and productivity information that the estimators come up with. Probabilistic estimating systems are available but they still depend upon reasonable judgments of low, high, target, and confidence values. Field personnel are continually wrestling with the problem of distinguishing between real productivity figures and apparent productivity figures (real productivity considers only those hours spent in direct or indirect productive work; apparent adds in lost hours not attributable to the worker, such as materials delays). Thus, there is considerable opportunity for research in methods for accumulating and cataloging usable data.

Improved methods are needed to handle uncertainties in activity durations and costs when planning projects. PERT is inadequate and has not been generally accepted in the construction industry; Monte Carlo simulation is computationally expensive. Any treatment of uncertainty must handle correlated variables efficiently; statistically independent variables are almost nonexistent. Yet methods for measuring or estimating correlations in practice do not exist either, and few construction professionals have much intuitive feeling for correlation coefficients. Methods for eliciting subjective estimates of correlation coefficients (or some other measure of dependence) from experienced personnel are needed, as the analysis and management of risk in construction is becoming increasingly important to clients and contractors.

The control process depends on comparisons of planned to forecast outcomes. Typical current forecasting models are ver y simplistic, such as progress reporting in CPM changing only reported activity remaining durations with subsequent floating of the remaining schedule. Cost forecasts are usually linear extrapolations and only on active cost accounts. Better methods are needed which recognize probable impacts on a broader basis than components on which change is directly reported.

With our ability to collect and process performance data more easily and broadly, we find a need for increased planning of expectations. Opportunities exist for automating more of this planning process. First by inferencing from CAD system databases on the content and process by which the project will be built, and second by extrapolation or modeling from experience on expert knowledge. These provide the basis for information constituting the "standard" for the control systems, with actual progress measured against this standard. Field data collection also yields research opportunities for potential automation providing validation processes are developed concurrently. The development of any data automation must provide an audit trail and adequate validation. Some of these issues were discussed under Integrated Systems earlier in this paper.

Proposed Research in this Topic Includes:

1 Planning and Control Under Uncertainty
- a) Analytic methods for contingency management which recognize correlation between risks.
- b) Methods of assessing correlation coefficients.
- c) Optimal contingency allocation in hierarchical planning procedures.

d) Impact of organization structure on contingency management, including determination of the basis for authorization on contingencies.
e) Development of new simulation models that provide conditional looping (rework and etc.) much like the GERT model but based on prior events.

2 Improved Forecasting Methods

a) Inclusion of experience modifiers in control systems.
b) Analysis of causes of variance from progress reporting data.
c) Methods of recording and including changes in project planning.
d) Generation of risk based mitigation strategies for project control.
e) Methods of forecasting Bulk Commodity quantities and their installation rates. (This should be stated in probabilistic terms including an error term.)
f) To combine deterministic and probabilistic capital expenditure modeling techniques with planning techniques to produce a computer based tool which can be used in the conceptual and feasibility study plans of large projects.
g) Development of total cost measures which combine inflation and financing rates through to macro productivity rates; appropriate techniques for making tradeoffs between rate of return, equity input, total cost, plant reliability and project duration; and practical approaches for measuring risk in the foregoing variables and using these measurements to select risk mitigation strategies.

3 Planning Procedures

a) Generation of CPM schedules from project CAD data and project organization charts.
b) Hierarchical cost modeling methods.
c) Application of cost modeling concepts to broader planning data.
d) Development of Standardized Modular sub-networks of common

field fabrication processes.

e) Develop Resource Models that provide a tradeoff between the cost of increasing resource utilization and consuming float which represents a decrease in future flexibility.

f) Marry the concepts of CPM with production line planning systems to allow for the treatment of both repetitive and non-repetitive activities.

4 Mega-Project Controls

a) Regulatory agencies are requiring Owner Organizations to demonstrate that prudent design, project control and overall management was employed on rate base mega-projects. Research needs to be conducted to determine prudent contract administration practice on these projects.

b) Determination of appropriate computer management tools sufficiently versatile to respond to the owner's cash flow and audit requirements, approval mechanisms, vendor preferences, etc.

c) Appropriate audit procedures for evaluating project management performance.

d) To develop formal methods for conducting post project analyses in order to transfer experience from one project to another and from one project manager to another, as well as to start toward the goal of representing "good construction practice."

5 Estimating

a) Successive estimating, decision theory, and other quantitative methods are potentially applicable for estimating material quantities in industrial construction. Material requirements are constantly being redefined from the time initial plot plans are developed to the time when final drawings are released for construction. The risk associated with placing material orders before all design information is available needs to be evaluated.

6 Automated Measurements

a) For construction controls as well as later facility management, as-built dimensional databases will become necessary. Improved techniques for automatic feedback of as-built locations and dimensions are needed. Stereo photogrammetry is one technique now being used, but is still labor-intensive. Better automated methods would reduce the costs of as-built databases (or drawings) and could provide more accurate and efficient dimensional control and positioning during construction.

b) Development of automatic scanning devices attached to microcomputers allowing direct input of foreman reports in real time so foremen can review while computer verifies badge numbers, work items and so forth. Research on how to best capture the data needed for existing control systems, e.g., transactions such as labor and equipment, timecards, material shipments, receipts and issues, activity starts and completions, work quantity progress, etc. The effectiveness of sophisticated control systems is often seriously limited by inaccurate and untimely input data. Research is needed to study alternative methods of capturing this raw data in an accurate, timely and cost effective manner.

7 Quality Control

a) Computer applications in construction quality control are urgently needed. Statistical quality control techniques, following W. Edwards Deming and the Japanese, could be adapted to construction site conditions.

COMMUNICATIONS

In the final judgment, the effectiveness of the design, construction planning and control, and final success in facilities management is in a large part determined by the project communications. The key issue in computerized project communications is the development of integrated project databases for communications between engineers, designers, fabricators, constructor s, and clients. Central to the computerized database are a three-dimensional graphical model of the project and the non-graphic attributes. A significant question is, who is to construct and maintain this database so that all other participants can have equal access to it?

The use of the computerized data base should permit the elimination or reduction of paper as the medium of communication. Research is needed into how this hypothetical paperless project would function. Details such as how to affix approvals and the professional engineer's stamp must be resolved.

Proposed Research in this Topic Includes

1 Graphics.

a) Research into appropriate graphic display of
   - financial and risk analysis
   - cash flow projections
   - control system variances

b) Rather than remaining dependent on the designers' drawings as the only representation of the project, construction personnel are using computer graphics equipment to generate drawings-on-demand from views of the three-dimensional graphical database. These representations are pictures rather than legal drawings. What status do these drawings-on-demand have? What improvements in graphical display devices to produce them are needed? What languages are needed to communication the desires of construction personnel to the database? How will such technological developments affect the design-construction process and the organization of construction firms?

c) How to make man-machine interaction more natural, i.e., touch screen or voice-activated input/output devices.

d) Creation and access to distributed data bases on a national scale.

SUMMARY

Many issues have been raised by the proposed workshop participants. A review of these should generate many more ideas. It is our hope that each participant will be prepared to discuss and expand on these proposals.

We wish to thank the contributors.

RESEARCH AREAS FOR THE APPLICATION OF KNOWLEDGE-BASED EXPERT SYSTEMS TO CONSTRUCTION ENGINEERING AND MANAGEMENT

WHITE PAPER
FOR
THE NATIONAL SCIENCE FOUNDATION WORKSHOP ON THE DEVELOPMENT OF NEW RESEARCH DIRECTIONS IN COMPUTERIZED APPLICATIONS TO CONSTRUCTION ENGINEERING AND NANAGEMENT STUDIES

May 19-21, 1985

Champaign, Illinois

by Raymond E. Levitt
Associate Professor of Civil Engineering
Stanford University

With input from:

David B. Ashley, Associate Professor of Civil Engineering, University of Texas at Austin
Hans Bjornsson, Director, Chalmers/Institute for Management Innovation and Technology, Gothenborg, Sweden
James Diekmann, Associate Professor of Civil Engineering, University of Colorado
Clive L. Dym, Professor of Civil Engineering, University of Massachusetts at Amherst
Robert D. Logcher, Professor of Civil Engineering, MIT
Mary Lou Maher, Assistant Professor of Civil Engineering, Carnegie-Mellon University
Michael J. O'Connor, Operations Research Analyst, Construction Engineering Research Laboratory, Champaign, Illinois
Kent A. Reed, Leader, Computer-Integrated Construction Group, Center for Building Technology, National Bureau of Standards, Gaithersburg, Maryland
Kenneth F. Reinschmidt, Stone & Webster Engineering Corp., Boston, Massachusetts
Richard Shaffer, Technical Director, Construction Engineering Research Laboratory, Champaign, Illinois
Geoffrey Trimble, Professor of Construction Management, University of Technology, Loughborough, UK

This White Paper attempts to provide an organized summary of the initial ideas of each of the participants in our workshop about the desirability and feasibility of conducting research in a number of areas related to the application of knowledge-based expert systems (KBES) to construction engineering and management. These suggestions have been grouped into seven major areas. We begin with an overview of reasons why same of the participants feel that KBES are especially applicable to construction engineering and management problems. The second section presents some thoughts on a guiding philosophy for research on KBES in construction, before getting into specific research areas. Section 3 discusses research on the tools that can be used for developing KBES applications in construction engineering and management. Section 4 raises the issue of research on knowledge acquisition methodologies – the art of building expert systems. Section 5, one of the longer sections, covers suggested application areas for KBES using existing or future tools. Section 6 raises the issue of standards for the testing and validation of KBES in construction and the final section, Section 7, proposes research topics to study the organizational, economic, and social impacts of KBES in construction. Finally, an appendix lists the names and affiliations of some researchers on expert systems in construction engineering and management that the author of this White Paper could easily develop. Delegates at this workshop are encouraged to add to this list so that we can assemble a working network of researchers in this field.

1. THE APPLICABILITY OF KBES TO CONSTRUCTION

Several researchers have pointed out that the nature of the construction industry makes expert systems especially applicable to construction engineering and management problems. In this industry, they point out, we have a high dependence on empirical rules, and on procedures derived fram experience rather than from a scientific knowledge base. They also point out that a number of inter-related disciplines and parties must interact, often with relatively little knowledge of the decision processes or rules of thumb used by other disciplines than their own. Furthermore, participants have pointedout that many tasks in construction have high training requirements for experience-based rather than conceptual knowledge, hence the use of long apprenticeship programs for training the crafts and for gradual accumulation of responsibility in the project engineering and project management ranks. Since the conventional wisdom may be ahead of scientific knowledge in construction, and since it is very hard to train new recruits when the knowledge of the conventional wisdom has not been formalized, expert systems may have an unusually large role to play in communicating the knowledge of more experienced practitioners to newer incumbents of those positions.

2. VIEWS ON A PHILOSOPHY TO GUIDE LONG-RANGE RESEARCH DIRECTION FOR THE APPLICATION OF KBES IN CONSTRUCTION

There is general agreement among the participants on some aspects of a research philosophy and clear disagreement in others. Let's begin with the areas where there seems to be considerable agreement. Participants stress that we should be trying to do more than build simple checklists with our expert systems, but should be trying to develop "cognitive maps" involving deep-domain knowledge, the ability of the system to learn from experience, and the ability of the system to handle a wide range of instructions or data related to the question at hand. There is also considerable agreement that we should devote significant resources to testing and validation of the knowledge in KBES, since their credibility to industry practitioners will be of key importance.

In addition, participants agree that mechanisms ought to be developed for sharing the results of KBES such that a global knowledge base could be developed and be made available for research or teaching purposes. This might involve standardizing on tools and/or developing standard rule or frame formats. One participant suggested that the focus of new applications should be where the state of practice lags the state of the art. As I interpreted it, this meant where one or more practitioners were more skillful or more capable than the majority of practitioners in the industry at some aspect of the construction engineering and management task. This participant also suggested that we focus where problem-specific information needs are the lowest, that is, on the generic kinds of problems where little specific data would be needed to determine the facts for a special case.

The sharpest disagreement among participants--and this will be a topic of lively discussion at our workshop--was on whether we should start by developing general-purpose problem-solving tools and techniques or whether we should attempt many small and specific applications in order to identify the directions for tool development. Participants are challenged to consider where we are now in the development of expert systems for construction applications and to form their own opinions about whether it makes sense for construction researchers to be working on the tools, relatively general applications, or more specific applications. Previous research has indicated that there appears to be a fairly sharp trade-off of depth versus breadth in applying expert systems.

A final thought on this topic which was mentioned by Steve Fenves at a recent Stanford lecture and which was also raised by one of our participants was that attempting to develop a KBES in a field could lead to the identification of new theory, or deep knowledge in the field, by formalizing the existing state of knowledge in a clear and unambiguous fashion. In this way expert system tools can provide heuristic answers to today's problems while suggesting research to develop algorithmic solutions in the future.

3. IDEAS FOR RESEARCH ON TOOLS FOR KBES APPLICATIONS IN CONSTRUCTION

Several participants stressed that expert system shells (empty expert systems) and AI-representation languages such as KEE or MYCIN should be favored over basic programming languages such as LISP or PROLOG because it was much more efficient to write in these higher level programming languages. At the same time, in partial contradiction to this, other participants suggested that researchers skuld work to combine expert system framework with other computer capabilities (e.g., computation, simulation, etc.). This should be another substantial topic of discussion at our workshop.

Recognizing the limitations of simple rule-based systems for significant construction engineering and management problems, participants have suggested several enhancements of existing KBES tools as valid research areas. The lack of satisfaction with current procedures for dealing with uncertainty in KBES led to participants proposing enhancements in the way that KBES treat certainty factors. Research is proposed on more robust methods for reasoning with uncertainty and for ways to update certainty factors with new knowledge gained through experience with the system. The issue of how graphical, spatial knowledge can be used in KBES was another proposed enhancement of existing KBES tools. Clearly, such a facility would permit interaction of KBES tools with CODD tools and would provide an interface to simulation and two-dimensional design or planning problems.

Several users proposed as areas warranting research the integration of KBES with other computer tools. Some participants proposed combining expert system with simulation or optimization techniques to permit intelligent set-up of a problem for analysis, or interpretation of results. Others proposed the need for expert system tools to interface with algorithmic proqram such as computer structural analysis packages. The integration of such high speed nor-crunching program witn AI programming environments is believed by these participants Co offer some synergy. Finally, as mentioned above, several participants proposed the integration of KBES with existing CADD tools to achieve of number of potential applications. This will be described in Section 5 below.

The use of expert systems which learn (i.e., they induce rules from cases or examples) was proposed by two participants as being a worthwhile area of research. For example, this might involve studying the properties of inductive algorithms or ways to vary the weights given to different examples or cases when inducing rules. Existing tools such as EXPERT-EASE do not permit this. Such inductive tools could search all data for patterns with these expert system equivalents of regression analysis, and possibly use these in combination with expert-generated rules.

Several participants have suggested the development of tools specifically for construction engineering applications. These might be single purpose, stand-alone tools for very specific applications, or "power packs," higher level languages within existing tool kits customized for construction applications.

4. RESEARCH ON KNOWLEDGE ACQUISITION METHODOLOGIES

Two of the participants suggested that significant research needs to be done on methods for acquiring the knowledge that goes into KBES. Some of the topics proposed for study include the development of improved protocols for interviewing, and of the roles of single versus multiple experts in contributing to KBES.

5. RESEARCH ON APPLICATIONS OF KBES WITH CURRENT OR FUTURE TOOLS

This is the area to which participants devoted most of their comments. These applications are listed in order of their applicability to phases of a construction project, starting from planning and design through construction estimating and bidding, hard finally planning and control, and facility operations.

5.1 Formalization/interpretation of contract terms and conditions. A preliminary KBES has been built by Construction Engineering Research Laboratory (CERL) of the Army Corps of Engineers in collaboration with the University of Colorado which attempts to diagnose whether a contractor has a valid claim under the differing site conditions clause of the federal contract. Other ideas include expert systems which could be used in formulation of new contracts under a variety of different conditions.

5.2 Planning and design of constructed facilities. In this area we have proposals ranging fram fairly general to quite specific. One participant suggests the development of formalisms for the representation of planning and design statements. This basic research in knowledge representation would permit others to develop design expert systems more readily. An alternative view suggests building more applications in planning and design to discover what works by experience rather than attempting to define formalisms in advance. (One of the participants in our conference has developed a fairly substantial design expert system, HI-RISE, and can share this experience with us.)

A third subject in the area of planning and design involves the integration of expert systems with CODD tools. Applications here range from expert systems which check applicable design codes in an interactive fashion, to expert systems which interpret design requirements from the client and requirements from other disciplines. One participant proposed research to generate construction plan and schedules with cost estimates fram early design data. Finally, expert systems are proposed as design checkers. In this mode, expert systems would use rules of thumb to check whether designs are in the right ballpark, the way a senior engineer would do a quick review of a subordinate's design.

In the area of ongoing design management, systems are proposed to carry out configuration management or design-change management. These systems would monitor the source and sequence of changing design criteria, would warn affected parties of design changes by other disciplines which might impinge on them, and would automate the redesign of affected components.

A final topic in the area of design involves analysis of the constructibility (British colleagues should read "buildability") of designs that have been developed. Such systems might range from very early cost-estimating systems such as are being developed in the UK at the University of Reading, through to very specific checks of detail design (such as a system to check whether a bolted steel connection has been properly detailed so that it can be easily fabricated and erected).

5.3 Cost estimating and bidding. Suggestions for expert system applications in this area range from systems for market forecasting through systems for the selection of jobs to bid, systems to evaluate bids, and systems for analysis of political and other risks (such as the Hitachi effort of which same of you may be aware). In the area of cost estimating, some proposed applications involve choosing the co-efficients which will be used as multipliers for the average historical labor productivity, given the particular conditions of the job-site under consideration. A second topic in cost estimating was mentioned above under CADD; that involves conceptual estimating of costs from CADD or other early design data.

5.4 Lay-out of temporary facilities on a job-site. Some early work has been published in this area and others have suggested it as a fruitful area for expert systems research. This is concerned with the two-dimensional or even three-dimensional lay-out of facilities such as storage, hoisting equipment, change shacks, material lay-down areas, access roads, etc., on a construction job-site. This is clearly an area where there is little formal knowledge and where experienced practitioners appear to do better than less experienced practitioners. Expert systems may provide a vehicle for spreading this knowledge.

5.5 Project planning and control. Participants have pointed out that construction is really quite different than automated manufacturing. We have more business entities, each with their own agendas and planning processes, we employ multiple resources, and that construction job-site changes dynamically. All of this creates a need for temporal reasoning.

Much of the knowledge used by managers in developing their schedules is not formalized. Scheduling tools use only the end-product of the planning process--the durations of activities and their sequential relationships. It is thus impossible to reason about this data without the input of the expert who developed the schedule. There seems to be wide agreement among participants that intelligent project planning "advisors" would be worth developing. These might provide systems in interpretation of status reports, improved forecasting methods, and ultimately automatic generation and regeneration of project plans using knowledge of the construction process.

5.6 Expert systems for managing human resources in construction. Among the topics proposed by participants are expert systems for designing project and company organization structures in construction, expert systems for advising on personnel procedures, and expert systems for labor relations. In the first area what is proposed is an expert system which would consider the situation of a project (that is, the goals of the participants in the project, the environment in which the project is to be executed, and the technology to be used for the project) and then to design an organization structure with the availability of suitably skilled participants as a constraint. Participants proposing personnel procedures and labor relations as topics need to provide additional background on their proposed research topics here.

5.7 Design and construction code interpretation. Work has already been done on interactive design program which use rules to interpret code requirements interactively. Participants have proposed that expert systems be developed to interpret fire codes (e.g., from the fire safety tree developed by the National Bureau of Standards), and expert systems for advising on strippinq of form work, shoring and reshoring during concrete placement. In addition, expert systems were proposed for code interpretation in the areas of welding and rigging.

5.8 Expert systems for assessing operating problems in completed facilities. This final applications area proposes expert systems to help diagnose the sources of leaking or condensation in completed structures, diagnosing malfunctions in HVAC system, identifying the source of radio frequency interference in communications systems, or identifying and remedying the causes of unacceptable levels of noise transmission in structures.

6. RESEARCH ON STANDARDS FOR TESTING AND VALIDATION OF KBES

More than half of the participants pointed out that the validation and testing of KBES is a significant issue which is worthy of research. Several of the participants pointed out that ultimate acceptance by industry of this tectology rests on the extent to which the knowledge in KBES is tested and validated. There appears to be no agreed-upon standard for testing or validating in a KBES. Should tests be geared to comparing how closely the KBES replicates the performance of a single expert, or should the tests be more global in nature? This area needs significant discussion, both as a research topic and as an issue in evaluating the results of ongoing research which we might carry out in any of the areas listed in this White Paper.

7. ORGANIZATIONAL, ECONOMIC, AND SOCIAL IMPACTS OF KBES IN CONSTRUCTION

Some people have suggested that KBES will have more of an impact on knowledge workers than robots will ever have on blue-collar workers. If this is the case, these participants suggest that research on sane of the implications of expert systems for the organization, economy, and culture of construction are in order. Some of the topics proposed include consideration of the issues related to developing a "community memory" through distributed knowledge via networks.

Other issues include questions of the control over data and knowledge bases in a project as we move towards "real-time engineering" (a machine-readable database which is constantly modified from the planning stage through construction and operation of the completed facility). Questions about the liability for the knowledge in an expert system and the ownership of the knowledge in an expert system are real ones. What about the willingness of experts with empirical knowledge to formalize this knowledge, thereby rendering themselves potentially less indispensible to the organization? These are interesting issues which could consume a workshop all by themselves. I will attempt to carve out some time for discussion of these issues during our two-day workshop.

CONCLUSION

This White Paper has attempted to capture and provide some organization to the excellent range of ideas generated by all of the participants listed on the cover. The source of individual suggestions has been deliberately left undefined so that nobody will feel the need to propose or defend any particular idea or ideas during the workshop. If any of our participants were unable to get their ideas submitted in time to be included in this White Paper, please bring to the conference 12 copies of your ideas organized, if possible, to conform with the numbering system in this White Paper so that these can be shared with all participants. The depth and breadth of the comments provided by participants were outstanding and we anticipate a fruitful and stimulating discussion.

APPENDIX: EXPERT SYSTEMS RESEARCHERS IN THE UNITED STATES AND EUROPE

Roger Allwood, University of Technology, Loughborough, UK
David B. Ashley, Associate Professor of Civil Engineering, University of Texas at Austin
Hans Bjornsson, Director, Chalmers/Institute for Management Innovation and Technology, Gothenborg, Sweden
James Diekmann, Associate Professor of Civil Engineering, University of Colorado
Clive L. Dym, Professor of Civil Engineering, University of Massachusetts at Amherst
Colin Gray, University of Beading, UK
Robert D. Logcher, Professor of Civil Engineering, MLT
Mary Lou Maher, Assistant Professor of Civil Engineering, Carnegie-Mellon University
Michael J. O'Connor, Operations Research Analyst, Construction Engineering Research Laboratory, Champaign, Illinois
Kent A. Reed, Leader, Computer-Integrated Construction Group, Center for Building Technology, National Bureau of Standards, Gaithersburg, Maryland
Kenneth F. Reinschmidt, Stone 6 Webster Engineering Corp., Boston, Massachusetts
Richard Shaffer, Technical Director, Construction Engineering Research Laboratory, Champaign, Illinois
Duncan Stewart, University of Technology, Loughborough, UK
Geoffrey Trimble, Professor of Construction Management, university of Technology, Loughborough, UK

researchers at Salford University, UK
researchers at University of Edinburgh, UK

others?

NSF/University of Illinois Workshop on
Computer Applications to Construction

May 19-21, 1985

Topic 3: ANALYSIS AND DESIGN OF SITE OPERATIONS

White Paper Edited by Boyd C Paulson, Jr.,
with Input fran Leonhard Bernold, Robert I. Carr,
Vir K. Banda, Weston T. Hester, Peter Lansley, and
Kenneth F. Reinschmidt

Introduction

This is a broad-ranging topic, but on the basis of input from the participants this paper will focus in particular on (1) communicating the CAD database from design to construction; (2) simulation at the site operations level; (3) simulation at the organizational level; and (4) automation of data collection and process control. Brief comments will also mention other types of quantitative methods, and the potential for supercomputers as a vehicle for such methodologies in construction.

Design Communications

Three participants interpreted the scope of this topic to include computer-aided design and/or drafting, especially as a direct means for communication between engineering design and site construction personnel, and also as a method of designing site layouts and performing other field-oriented tasks.

Hester lamented the fact that "a CAD system may be used to generate a drawing on paper, but the drawing and not the diskette or other electronic media is sent to the field for construction purposes." He then provided a good summary of the potential applications and benefits of such methods as follows:

> Use of a microcomputer-based CAD system in the field and design offices can facilitate constructibility reviews, help identify potential interferences of the work in the field, and help communications between field and design personnel. With a CAD system, the engineer can view a detail on a computer monitor and add, delete, or change any item, and zoom up or down to any scale. This facilitates constructability reviews and identification of potential interferences. If two microcomputers have the same software, they may both be used to view the same detail simultaneously. This permits a quick exchange of ideas and revised drawings between the field and design office.

Handa also addressed this subject, and added the following possibilities:

> There is no reason why there could not be linkages between CAD at office and site so that there are updated drawings at all times available at site, leading to reduced or no rework. Similarly site corrections could be fed back into CAD drawings giving complete as-built drawings. They could also be useful in providing isometric/3D drawings as against orthographic, and with proper equipment have large-scale projections for job-site production analysis and use by site personnel. The ability to change scale and zero in on a particular item is especially useful. It would be most helpful in giving early warning of future problems (interference, for example) or else availability of needed materials in inventory, and thus productivity impact.

Focusing more on site layout, Reinschmidt confirmed that "some contractors have developed optimization programs to determine the site layout that minimizes travel time, or other economic parameters, based on assumed travel matrices."

<u>Needs</u>. Turning to future needs in this area, Reinschmidt went on to point out same current problems that must be overcame:

> Little feedback is available on how site layouts actually function, actual trip frequencies, delays, or other performance factors. Owners are not highly motivated to demand efficient site layouts, although studies have shown that layouts minimizing travel time can substantially reduce lost time. Fundamental industrial engineering studies on how site layouts perform are essential to the development of improved computer methods for site design.
>
> Methods for integrating site operations models with the three-dimensional graphical data base are needed. Procurement, fabrication, and installation dates from project schedules should be identified as attributes in the database model. The design database could then be used to generate graphical depictions of alternate construction sequences for constructibility review and construction planning.

Hester added the following needs:

> (1) Software utilities through which alternate CAD software systems may be integrated with the existing mainframe and minicomputer systems should be developed; (2) Alternate methods for using CAD systems to model construction operations, including construction sequence and equipment configurations should be developed (this may mean, for example, integrating some mathematical simulation programs into a CAD display); and (3) Alternate approaches to integrating CAD systems with existing design programs and other software packages, such as spreadsheets and database programs, should be developed.

Site Operations Simulation

State of the Art. This topic was at least mentioned by all contributors, and was the main focus of the submissions by Bernold and Carr. To keep things in perspective, Lansley offers the following view of the present state of the art:

> Simulation in construction is mainly occupied with the development of operational models of project "sub-systems." Most models have been developed to provide a better understanding of the implications of management decisions for time and cost of construction. Often these models are used to seek some "optimum" solution to the utilization of scarce or expensive resources. At the operational level these models can be very helpful both as an aid to decision-making and as a means for developing an understanding of the system which has been modeled. The art of such "sub-system" modeling is sophisticated and mature.

Lansley also submitted the results of a CIB survey by Roy Pilcher (attached).

Carr summarized current research and needs in this area in the following points:

- Applications of general simulation programs: GPSS, GERT, SCRAM, SIMSCRIPT, etc.

- CYCLONE-based simulation: microbased (Georgia Tech, Michigan); with costs (Georgia Tech, Michigan); resource-based (Michigan); integration with data collection (Stanford)
- Dedicated simulation programs: SCRAPESIM (Penn State); tunnel model (MIT)

- Integration with graphics: graphic display of process during simulation; depiction of results

Bernold also summarized current research as follows:

> Our efforts at Georgia Tech address some of the above-mentioned issues. In particular, these are extended computerized simulation of construction processes; integration of process and project scheduling; automated data collection; and computerized project control system. There are three other major research teams who work in similar areas. These are teams under Boyd Paulson at Stanford University; Ronald broadhead at the University of New South Wales in Australia; and under Jose Lluch at the University of Puerto Rico. Further contributors are Bob Carr at the University of Michigan and Dick Larew at Ohio State University.

To broaden these views somewhat, Lansley described other important efforts in Great Britain:

> In the U.K. the most significant efforts in simulation seem to be at Reading (project management simulator and company simulator – AROUSAL) and at UMIST (project-based simulators - Pilcher). Also, there are a number of consulting companies with extremely sophisticated project simulators which have been developed for specific purposes (e.g., management of North Sea oil rig construction and production). I will seek more information. One approach which I have been conscious of for some time, but which I have not been able to evaluate in terms of its usefulness for studying construction, is that developed by R. Burton and B. Obel for analyzing and designing organization structures. It uses an LP-oriented decomposition algorithm. theoretically – elegant. Practically – either powerful or useless!

Future Needs for Operations Simulation in Construction Needs in this area were addressed by three contributors. We will begin with a statement by Lansley:

> The flexibility and tunability of simulation models needs to be improved so that they can be handled by the practitioner as a routine tool for decision-making. The need is for user-friendly authoring systems which enable the occasional user of simulation models to build models of specific systems (e.g., companies, total projects, or parts of projects) both rapidly and without any special knowledge. Such systems need to gather data in ways which are meaningful to the user, and to translate that information into the framework used by the simulation system. At the moment a common problem is that simulations require the practitioner to think in new ways. While thinking in new ways may be desirable, in the short term some bridge must be built between the "old" worlds in which practitioners/managers live and the "new" worlds which we would like them to inhabit.

Bernold seemed in tune with this view in the following statements of need:

> The problem of user-friendliness of computer systems and human/machine relations are topics for the human resource factor. Since the human is the ultimate user and feeder of computers, we shouldn't forget this central issue. Computer simulation should be geared to help the construction manager to optimize during planning as well as during actual construction. Another area for further work should be the integration of process and project scheduling. Such a system would be especially beneficial in the planning and design phase when different technologies could be simulated and their impact on the overall project schedule quickly analyzed.

Reinschmidt added the following:

> Computer simulations of repetitive site operation, such as excavation and grading, are frequently made but are computation and data intensive. Improved simulation tools for evaluation of different methods and processes, that would be easier for construction personnel to use, graphically driven, and less dependent on detailed data, are needed if computer simulation is to be of great practical use in construction planning. In general, improved practical techniques for verification and validation of computer simulation models are essential.

Organization Level Simulation

Lansley focused quite eloquently on this area, and made a very strong case. His words speak for themselves:

> Those models which are in need of further development (in some cases pioneering development) are those which provide a strategic rater than an operational view of project behavior. Such a strategic requirement is present at both the total project level and at the corporate level (i.e., multi-project level) within construction organizations. There is also a similar need at the macro/governmental level (e.g., at the point where major infrastructure prospects have a significant impact on a regional economy--where OR simulation meets econometrics).

He also did an excellent job of summarizing the important needs in this area:

> Major issues (which should be) addressed are: methods which integrate and synthesize existing sub-models, which are able to place these in their appropriate contexts (for example, in terms of relative significance to total project performance) and which identify important missing sub-models. Important among the missing sub-models are those which address organizational and human parameters. Traditionally, simulation models have been built around theories from the OR world, not around those from the social sciences or from psychology. Yet many models of human behavior are amenable to being expressed in simulation terms. Also, there is a wealth of data which could assist the building of such models. What is lacking is some familiarity with behavioral models, and consequently confidence in building simulation models which incorporate human behavior. The essence of the point above is that to facilitate the wider utilization of simulation systems some thought has to be given to the way in which managers learn and solve problems. Simulation tools have to be presented in a way which capitalizes on preferred styles of learning and problem-solving. While practitioner acceptance is an important issue (which requires the simulation modeler to take an interest in other fields), there is also the opportunity to use simulation systems (as simulators) for studying how managers learn, solve problems, and make decisions. The information which can be

gathered from observing managers using, for example, project and company simulators can be extremely rich for the further development of simulation systems and for understanding _how managers manage_. Clearly _computer graphics_ have a very large part to play in facilitating practitioner acceptance, as well as providing an important tool for the specialist model builder. Some of the most exciting advances in the application of computer graphics can be found in those areas where designers are able to use simulators linked to graphics systems to convey their ideas to, for example, the non-specialist (e.g., their clients). Similar comments, although with some reservations, can also be made about the likely impact of _expert systems_. The issues outlined above largely relate to the content of simulation systems, their form of presentation, and their uses in a decision-making context, rather than to the other ways in which they can be used (although this is implied by some of the statements). However, my main concern is with the extent to which simulation systems can be used as a tool (e.g., as simulators) for management and _organizational development_. A new set of issues is raised by this interest. these question the _role_ of the simulation exert and the extent to which existing and future simulation systems may be under-exploited because of the lack of recognition of the contribution which (specific types of) simulators can make to the broader development of organizations.

Automation of Data Collection and Process Control

Several contributors addressed this topic. We'll begin with Handa to provide an introductory background:

> Computers are already being used in some of the above areas but their applications can be increased to have real-time management and progress analysis of construction projects, for example, spreadsheets for status of project costs and analysis on demand; simulation programs - albeit at a level that everyone on the site can use; for what-if's analysis with respect to management options from result of foremen delay/activity surveys; analysis of change orders, their pricing and schedule impact; etc. Inventory boxes used in supermarkets could be helpful in inventory control and even project progress management.
>
> Both graphics and non-graphics computers could be linked to display automated data capture, be it in engineering analysis or management terms. Means of data capture could be video, audio, or other. Video has been in the form of cameras and video cameras and audio by the use of microphones and other devices. The latter are being routinely used by others but not by construction where each machine has its own audio pattern and thus is easily distinguishable and traceable. Some mine/tunnel applications are on record. Types of sensors that could be useful need to be researched and studied.

Reinschmidt illustrated several additional areas of need for automation at the construction jobsite:

> Graphically oriented systems for positioning, operating, moving, scheduling, and control of cranes would be particularly useful. Efficient methods for extraction of data from time-lapse photography (or move up to data-video imaging) to generate computer models of site operations would be useful. Analysis of time-lapse photographs is labor-intensive, and the use of image recognition, scene analysis, or similar technology to create computer models would greatly enhance the use of these techniques. Automatic tracking of construction vehicles and equipment by means of satellite positioning (such as General Motors proposes for automobiles) or local transponder fields would provide feedback to computer models of equipment use as well as real-time monitoring of construction operations. More economical positioning systems and associated computer software are needed.

Bernold also provided several examples of needs:

> In the area of material I see opportunities for computerized and automated material-handling systems. Such a system would not only control the flow of material but also allow cost optimization and quality control. Furthermore, it would allow testing of different strategies in connection with a site ard process simulator and could be used as a tool to control construction progress. For equipment and tools, the collection and analysis of production and performance data seem to me the most important objectives. This database system would be the foundation for the analysis and design of new projects. Generally the computerized planning, scheduling, and monitoring of equipment and tools should be more emphasized. A computerized process control system which includes a feedback loop would incorporate some of the above-mentioned research areas.

Other Quantitative Methods

Although most concentrated on the topics which have been presented, Carr mentioned the following additional possibilities:

> (1) Estimating operation costs (i.e., integration with simulation to produce realistic costs for interactive processes); (2) Time/cost trade-off of operations which share costs (i.e., integer programming approach to relate costs to methods, resources, strategies which are shared by several resources [Michigan], and integration of resource allocation and time/cost trade-off for operation estimating); and (3) Control of operation time and cost (i.e., real-time feedback for time and cost control).

Role of Supercomputers

In this section the editor will offer an opinion which might be the subject for same discussion during the workshop:

First, tools such as computer-aided design and simulation modeling, at least as they apply to construction, have their primary focus on analysis and design for problem-solving. As such, they should be closely and interactively coupled to the human mind to best combine human judgment, experience, and intuition with the computer's strengths in rapid and precise computations and information-handling. Technological advances in small but powerful computers have facilitated this human/computer problem-solving with responsive interaction, graphics interfaces such as windowing (Lotus 1-2-3, MacProject, etc.), pull-down menus, and I/0 devices such as the mouse. These trends are continuing in advanced AI machines such as those male by Xerox and Symbolics, and seem to be the logical path of development for interactive problem-solving.

In contrast, supercomputers more closely resemble their batch mainframe ancestors, and their primary emphasis is on processing speed for large-scale computations. Their accessibility and economy for the average construction user is questionable, their human interface will likely remain user-hostile for some time, and it seems improbable that many construction applications will be handled in this way. It seems more likely that this kind of hardware power will migrate down to the desktop microcomputer level than it does that well engineered human-interactive software will move up to the supercomputers. Current technological trends will put Cray-like power on the desktop by 1995, but mainframe software will evolve at a glacial pace by comparison.

'Nuff said.

Conclusions

(to he developed at the workshop)

Attachment

Roy Pilcher's survey of simulation

CIB - National Council: For Building Research and Documentation

Working Commission W-65 – Orqanisation and Management of Construction

Summary of Questionnaire on Simulation in OMC (by R. Pilcher)

The following summarises, as far as possible, the responses to parts of the questionnaire which was circulated to provide a basis for those persons who may be interested in participating, by correspondence, in a working group concerned with simulation in the organisation and management of construction. Ninety-six questionnaires were distributed on a world-wide basis to individuals having a general interest in construction (not necessarily in construction management or in simulation). Those individuals were listed from a variety of sources and the list included those having a known interest in simulation in the field of construction. Thirty-two responses were received; a small proportion of questionnaires were known not to have been delivered through change of address, etc. Of the thirty-two responses, only two individuals indicated that they would not be interested in working with any such group that was formed.

Certain of the questions were an attempt to identify current work in construction simulation. It is now proposed to obtain an elaboration of those responses and to produce a further summary in due course.

The analysis of those questions that lend themselves to simple arithmetic quantification are as follows:

Question 1

Serious practitioners	16
Occasional practitioners	6
Interested skeptics	4
Afraid of missing something	5
Don‘t know	1
	32

Question 2

Active participant	12
Active if interested	17
Receive papers only	3
	32

Question 3

Question 3 was concerned with particular interest in specific areas o: the terms of reference.

Promotion of known studies	5
Test data availability	1
Identification of practical applications	1
Establishment of state-of-the-art	1
No preference	24

Simulation studies undertaken or in progress

1. The dynamics of the Swedish construction industry.
2. Simulation of construction operations (time lapse, simulation and CAD).
3. Gaming simulation of construction.
4. Financial simulation of a construction firm.
5. Application of Micro-Dynamo to building prospect dynamics.
6. System dynamics simulation, research and consultancy with regard to marketing studies for building materials supply and demand.
7. Housing supply, demand, ageing of the building stock, maintenance, energy scenario's, etc.
8. Shelter design and analysis.
9. Land subdivision, utility network and affordability shelter.
10. Sector layour planninq, design and optimisation studies.
11. Time cost models for construction projects with resource constraints. Solution of problems by heuristic methods on micro-processors and by integer linear programming.
12. Simulation of the housing requirement on a regional basis (part of a larger prospect concerninq improved planning of building activities).
13. Monte Carlo methods applied to construction cost and/or time.
14. Equipment travel time simulation.
15. Simulation of construction operations.
16. Simulation for estimating scraper production.
17. Allocation of construction resources using process simulation.
18. Evaluation of productivity using process simulation.
19. Project management guidelines.
20. AROUSAL - a highly flexible simulation system having a wide range of management development applications through simulatinq the world of the senior management team of a medium sized enterprise.
21. Use of microcomputers for project management to include bidding analysis, scheduling, cash flow analysis and cost control.
22. Simulation of mutli-professional team work in the "identification" and "preparation" stages of the project cycle.
23. Development of a simulation language for use with a microcomputer (Apple II and PASCAL).
24. The development of parallel multi-microprocessing for use with simulation of construction operations.
25. The design of simulation computer models by direct visual input through VDU.
26. Development of a simulation program for application on the sites by the project manager or site agents.
27. Cost-modelling system for the construction industry, using database techniques and communicating with systems for CAD (MEDUSA or GDS).
28. Research and teaching for CYCLONE-INSIGHT operations simulation.
29. Use of management simulation games in teaching.
30. The use of GPSS to simulate construction equipment system operation; direct student research in network simulation and other simulation of construction operations.
31. Computer simulation of earthwork operations.

Robotic Applications in Construction White Paper on Research Issues[1]

Daniel R. Rehak2[2]

1. Introduction

The potential for construction robotics is widely recognized and is now being explored. The construction process has several aspects which make robotic applications idea: the hazardous nature of the construction environment, workpieces whose size is incompatible with humans workers, repetitious and physically demanding work, routine exposure to harsh environmental conditions, access to the workplace which is often severly constrainted, etc. Manufacturing robotics technology may not be directly transferred to construction, even if this were desirable. Potential problems include: the instability and unstructured nature of the construction environment, a harsh environment for robotic equipment, tasks which are not highly repetitive, tasks with are spatially disparate, and a design and construction process not attuned to robotic construction. While several research and development projects are underway, the range, applicability and future directions of construction robotics are indeterminate. The current state-of-theart, and a number of fundamental issues in the application of construction robotics are outlined below.

2. Current Robotic Applications in Construction

Table 1 is a partial list of institutions and researchers currently active in construction robotics and related areas, and represents several diverse projects and construction robotics applications. U.S. and European research and development is confined to a few universities, government laboratories and industries. Japanese work is most advanced (beginning in 1978 and now moving into field prototypes) with substantial research and development commitments from the major Japanese construction firms.

3. Motivation for Construction Robotics

Three key issues often stated as motivations for construction robotic are listed below. In all three, there is an underlying theme based on the hazardous, harsh nature of the construction process and the construction environment.

- Economics. Robotics implies increased productivity and reduced costs. Due to the labor intensive nature of construction (with laborers performing strenuous tasks in a harsh environment) and the continuing decrease in productivity, automation looks attractive. However, it is unclear how the productivity of workers will be affected and to what extent construction tasks can be reorganized (if this is appropriate) to exploit robotic technology. It should be noted that Japanese firms report robots are more costly than the humans they replace and the actual cost savings associated with robotics comes from secondary aspects such as reduced material costs through better quality control.
- Quality Control. Humans are not good at performing repetitive tasks or actions requiring

[1] Prepared for NSF Workshop on New Research Directions in Computerized Applications to Construction Engineering and Management Studies, University of Illinois at Urbana-Champaign, Urbana, IL, May 19-21, 1985.

[2] Assistant Professor, Department of Civil Engineering, Carnegie-Mellon University, Pittsburgh. PA 15213, DANIEL.REHAK@CMU-RI-CIVE.ARPA

Table 1: Current Construction Robotics Research Activities'[3]

Construction	Battelle Laboratories Carnegie-Mellon University: Whittaker, Sangrey, Fenves, Rehak Georgia Institute of Technology: Halpin, Kangari Japanese Constructors: Kajima, Takenaka, Smizu, Ohbayasi-Gumi, Kumagi Gumi, Hazama Gumi Massachusetts Institute of Technology: Maser, Marks, Baecher, Logcher National Bureau of Standards: Albus, Hill? Stanford: Paulson Technion: Warszawski U.S. Army Construction Engineering Research Laboratory
Firefighting	Project Jupiter: Shirai
Forestry	??
Mining	Carnegie-Mellon University: Oppenheim, Whittaker, Maher Colorado School of Mines Massachusetts Institute of Technology: Peterson Pennsylvania State University U.S. Bureau of Mines
Nuclear	Carnegie-Mellon University: Whittaker, Rehak, Oppenheim Japanese Constructors: Kajima, Hitachi, Mitsubishi, Toshiba Kernforschungzentraum, Karlsruhe, FRG: Koehler Odetics
Space	Dornier, FRG: Siemann Massachusetts Institute of Technology: Sheridan NASA Langley Research Center
Undersea	Massachusetts Institute of Technology: Sheridan University of Warwick, UK: Larcombe Japanese: Komatsu

significant accuracy. The nature of the construction environment compounds there problems. As a result, construction quality and costs suffer. Due to their accuracy, improved, consistent quality can be achieved when robots are used in construction. Improved quality control is identified by the Japanese as a major incentive in developing construction robotics.

- Safety, Construction is a dangerous activity. Workers are injured in accidents and are affected by harsh external conditions. Robots can replace humans in performing tasks with a high risk of injury, or which are undesirable. In addition, robots can be used to explore and exploit new areas of application, such as space and underwater construction, where it is too dangerous for humans to operate.

[3] This list is based on information provided in the position paper by Greg Batcher, supplemented with my own information. It is not complete.and some items may be in error.

4. Problems Facing Construction Robotics

A number of issues and associated subproblems impacting the development of construction robotics are listed below. Each of these items currently are open research problems, and they must be addressed to insure a successful application of robotics in construction. However, the field is too new for any such list to be exhaustive, and a detailed presentation and organization of these issues has yet to be developed. In addition, many fundamental problems relating to the definition of the scope and range of construction robotics remain.

- **Construction Robotics Technologies**. A variety of technological issues relating to the selection, design and use of construction robotics and their components have to be considered. These include determining the special needs in construction robotics and the options for the various components of a construction robot. A partial list of such technological. problems is given below. The range of detailed technological issues to be considered in developing a construction robot currently is too open and new for any such list of aspects to be exhaustive.
  - *Sensors and Sensor Interpretation*. Sensors are an important part of a robotic system, providing feedback froam the world of the construction environment to the control system. A variety of sensors (tactile, vision, magnetic, sonar, proximity, etc.) may be useful in construction. What sensors are most appropriate for various tasks. How should raw sensor readings be interperted and converted into meaningful data for use by robots. Sensor technology is still in its infancy, and much work remains.

  - *Manipulators and Effectors*. Manipulators and effectors perform the actual tasks. What are the various options for manipulator design. How is compliance dealt with. What effectors are best for which tasks. How can workpieces be modified to aid effectors and manipulators. In addition, manipulator and effector designs are compounded by environmental conditions, large forces and wear.

  - Compliance. The compliance (deflections and structural dynamics) of both robots and the objects being handled must be considered, both in robotic design and operations and in component design. Forces generated and loads may be orders of magnitude larger then those dealt with in conventional manufacturing robotics. Compliance, tolerance and accuracy issues combine to create a unique problem in construction robotics. Manipulator design and control strategies (real-time, nonlinear finite element analysis of manipulator dynamics appears intractable) for use in construction robotics have to be developed.

  - *Environmental Impacts on Hardware*. The nature of the construction environment influences the design and operation of robots. Construction robotic equipment is subjected to excessive vibrations, dust, and extreme temperatures, humidity, radiation, etc. Robots must be tough enough to withstand the harshness of the environment and of the weather if outdoor work is to be performed.

  - *Mobility*. Construction robotic equipment needs some sort of mobility to deal with the unstructured nature of the environment and the diversity of work locations. Is full mobility needed or can conventional robots be used in construction. What options are available to support mobility and locomotion around the construction site. How is navigation supported. How is obstacle avoidance and the interaction with other workers treated.

- *Control*. Control systems provide the intelligence to guide a robot through a task. For autonomous or semi-autonomous robots, what control structures are used. How are task planning, navigation, sensor interpretation, obstacle avoidance, etc., handled. What are the algorithms, data structures and procedures for control processing tasks. Construction robots may need to have intelligent controllers to deal with the unstructured nature of the construction process and environment. What is the role of knowledge-based expert systems and artificial intelligence in providing this intelligence. What type of domain models can be used to support control and planning.

- **Applications**. Potentially, a variety of construction tasks can be automated. How are robots best applied in the construction process. What tasks are the best candidates for automation. Should there be full or partial autonomy, and what is the role of automation in conventional construction equipment. How do robots mix with human workers What are the off-site (rebar fabrication, shop welding, etc.) tasks which should be included in the domain of construction robotics. How should tasks such as materials handling, inventory control, etc., be dealt with in a robotic environment. The range and scope of construction robotics applications still has to be explored.

- **Unstructured Environment**. The construction environment is more unstructured, dynamic and complex in nature than the manufacturing environment. Tasks are performed at a number of locations, there is little standardization and repetition of tasks, every project is has some distinctive features, interactions are indeterminate, the environment is constantly changing, workers perform a variety of skilled manual tasks, worker turnover is high, etc. These aspects imply a number of needs for construction robotics, including. mobility, adaptable intelligent control systems, reconfigurable robots, etc. Potentially, the construction site can be reorganized or restructured to support robotic applications. In addition, the construction site can be rigged with sensor targets, site location reference systems, etc, to aid robots in performing tasks. Proper methods and techniques for dealing with the unstructured construction environment must be investigated.

- **Feedback from Robotic Construction to Design**. Design for robotic construction may be different from design for current construction methods. How will the introduction of robotics impact construction. Is there a fundamental difference in the process of robotic construction from conventional means. What should be done to tailor the construction site and construction process to robotic applications. How should the design of facilities, components, materials, equipment, construction processes, etc., be reorganized to support robotics. Is there a need to fundamentally rethink construction. How are computer-aided engineering and computer-integrated construction systems integrated into the robotic construction process.

- **Societal**. Acceptance of robotics by workers, management, and owners is necessary if their full potential is to be realized. Societal and labor implications are often stated as a detriment to the introduction of construction robotics, but their importance in not universally agreed upon. The emphasis on robots performing hazardous, undesirable tasks is sometimes used to circumvent these concerns for acceptance. However, the Japanese's desire to introduce robotics is related to a shortage of skilled construction workers, and labor acceptance is not considered to be such a significant problem. The nature of the acceptance problem and associated issues, such as worker retraining, needs to be considered.

5. Research Directions

Research in construction robotics can be divided into three general, although not uncoupled, areas. These along with a few specific research topics to be pursued are listed below.

- Robotic Systems. What are the proper components of a construction robot. What types of semi-autonomous and automated equipment can be used in construction and how do construction robots evolve from conventional construction equipment. What are the appropriate manipulators, sensors, effectors, mobility systems, control systems, etc., for the diverse variety of construction tasks and environments.

- Robotic Construction Process. How does the introduction of robotics impact the overall technical aspects of the construction process. What is the proper mix of robots and humans, what tasks should be robotized, how are the construction site and construction tasks reorganized for robotic construction, how are workpieces changed, how should the unstructured construction environment be dealt with, etc. How does robotic construction influence the design process and what is the link between robotics and computer-integrated construction.

- Socio-Economics. What are the impacts of robotics on labor, management and owners. What are the economic benefits of robotics and what methods should be used to the asses economics of construction robotics. How should robotics be introduced. What mechanisms should used in training workers and management.

As outlined above, construction robotics is ripe for further research and there are a variety of diverse research topics and open research problems. However funding and technology transfer from research institutions into practice must be addressed to institute a successful, cooperative university-industry research and development program.

Acknowledgements. The information above is based, in part, on the references listed below and on the position papers provided by: Greg Baecher (Massachusetts Institute of Technology), Photios Ioannou (University of Michigan) Roozbeh Kangari (Georgia Institute of Technology), Gene Leach (Caterpillar Tractor), Ken Reinschmidt (Stone and Webster), and Abe Warszawski (Technion). Space constraints limited the inclusion of many excellent topics introduced in these position papers.

References

Sangrey, D.A., ed., Robotics in Construction, Proceedings of the Workshop Conference on Robotics in Construction, Civil Engineering and Construction Robotics Laboratory, Robotics Institute and Civil Engineering Department, Carnegie-Mellon University, Pittsburgh, PA, June, 1984.

Warszawski, A., Robotics in Building Construction, Technical Report, R-84-147, Civil Engineering arid Construction Robotics Laboratory, Robotics Institute and Civil Engineering Department, Carnegie-Mellon University, Pittsburgh, PA, July, 1984.

APPENDIX B

WORKSHOP SCOPE AND FORMAT

EXHIBIT A: SCOPE STATEMENTS OF WORKING GROUP SESSIONS

Topic 1: Computer Applications to Project Communications, Design, Planning, Construction and Control.

This topic is scheduled first because it is the overview of the access, structure, content, and maintenance of project-wide databases as to be used by all project participants. These databases would include graphical, numerical, and textual information. Automatic registers and logginq functions are envisioned to track architectural programming and conceptual design decisions, structural resolution answers, change orders, submittals, and the logical interface to the other workshop topic areas. Research bounds would likely include databases and analytical advances in probabilistic scheduling theory (various distributions, correlations between variables and activities, "ripple" effect modeling); range estimating (modeling of different levels of estimates and their transitions, successive approximation techniques, value of better or perfect information); decision theory (e.g., risk attitudes and their application/impact on project decision, fuzzy sets); and protect simulation (nonsteady state processes, correlated variables).

Topic 2: Knowledge-Based/Expert Systems

This session explores the potential and specific durations in which the Artificial Intelligence (AI) techniques of knowledge-based systems including expert systems can be used in Construction Engineering and Management studies. Possible areas include:
(1) constructability reviews; (2) organizational development and structuring; (3) cost and schedule control and forecasting; (4) contrac dispute avoidance and resolution; and (5) dynamic project site planning and management. Discussion will be directed at reviewing early experiments in building such systems in construction and the limitations that have been found with existing tools and systems in the areas of: (1) modeling and representation of knowledge; (2} reasoning, deduction, and problem solving; and (3) heuristic search procedures.

Topic 3: Computer Applications to Analysis and Design of Site Operations

The scope of this topic would include computer graphic simulation of project operations and layout; applicability of mathematical programming concepts; integration of site-developed information (e.g., foreman delay surveys); and computer-based data acquisition and processing.

Topic 4: Robotic Applications

This session shall define the basic research issues concerning robotics and automated equipment and processes applied to construction. Its focus will include specific applications, basic technological issues such as sensors, mobility, control, large-force robotics, integrated systems, and ancillary issues including safety, industry acceptance, socio-economic concerns, and "design for constructability."

EXHIBIT B
WORKSHOP SCHEDULE

May 19, Sunday

Arrival of participants and registration at University Inn; Urbana, IL

4:00-6:30 Software Demonstration and Exchange Period

May 20, Monday

8:30-9:00	Welcome Specific Charge to Participants Workshop Format Outline
9:10-10:20	Small Work Group Session
10:20-10:35	Break
10:35-12:00	Small Work Croup Session
12:00-1:30	Lunch and Discussions of Prevailing Computer Environment Configurations
1:30-3:00	Report Session
3:00-3:30	Break
3:30-5:00	Report Session
5:00-7:00	Informal Get-togethers
7:00	Dinner and Discussions

May 21, Tuesday

8:00-9:30	Report Session
9:30-10:00	Break
10:00-11:30	Report Session
11:30-12:30	Lunch and Discussions of Construction Consortium Feasibility
12:30-1:45	Small Work Group Session (Summary)
1:45-2:00	Break
2:00-3:00	Workshop Summary and Closure

APPENDIX C

WORKSHOP PARTICIPANTS

GROUP 1

Prof. Keith C. Crandall — PANEL LEADER
Department of Civil Engineering
213 McLaughlin Hall
University of California
Berkeley, CA 94720

Prof. L. T. Boyer — PANEL LEADER
3149 Newmark CE Lab
208 North Romine Street
University of Illinois
Urbana, IL 61801

Prof. Robert Logcher
Dept. of CE
MIT
Cambridge, MA 02139

Prof. Chris Henrickson
Dept. of CE
CMU
Pittsburgh, PA 15213

Dr. Paul Teicholz
Guy F. Atkinson Co.
10 West Orange
South San Francisco, CA 94080

Prof. John Bennett
University of Reading, Berkshire
P. 0. Box 219
Whiteknights, Reading
RG6 2BU
ENGLAND

Prof. John Melin
3142 NCEL
208 N. Romine Street
University of Illinois
Urbana, IL 61801

Prof. Allen Russell
Dept. of CE
Univ. of British Columbia
2324 Main Mall
Vancouver, BC V6T 1W5

Mr. Gerald J. Landsly
N. E. O'Neil Construction Company
2751 Clybourn Avenue
Chicago, IL 60614

Mr. Francois Grobler
Department of Civil Engineering
University of Illinois
Urbana, IL 61801

GROUP 2

Profesor Raymond E. Levitt — <u>PANEL LEADER</u>
Dept. of' Civil Engineering
Terman Engineering Center
Room 298
Stanford University
Stanford, CA 94305

Dr. Kent Reed
Building 226, Room B306
National Bureau of Standards
Gaithersburg, MD 20899

Prof. Jim Diekmann
Dept. of Civil Engineering
University of Colorado
Boulder, CO 80309

Prof. Geoffrey Trimble
University of Technology
Loughborough, Leicester
ENGLAND LE113TU

Dr. Hans C. Bjornsson
Chalmers Inst. of Tech.
IMIT
F-41296
Goteborg, Sweden

Prof. David Ashley
Dept. of CE
ECJ 5.200
Univ. of Texas
Austin, TX 78712«1076

Prof. Mary Lou Maher
Dept. of Civil Engineering
Carnegie-Mellon University
Pittsburgh, PA 15213

Mr. Mike O'Conner
USA-CERL
P. 0. Box 4005
Champaign, IL 61820

Dr. Maria Adelaide Parisi
Politecnico Di Milano
Dipartimento Di Ingegneria Strutturale
P.za L. da Vinci n. 32
20133 Milano (ITALY)

Mr. Chuck Williams
INFERENCE CORP.
5300 West Century Blvd.
Los Angeles, CA 90045

Professor John Slater
Dept. of Civil Engineering
M.I.T.
Cambridge, MA 02139

Mr. Jesus Ma. De La Garza
Dept. of Civil Engineering
University of Illinois
Urbana, IL 61801

GROUP 3

Prof. Boyd C. Paulson Jr.
Dept. of Civil Engineering
Terman Engineering Center
Stanford University
Stanford, CA 94305

Prof. Robert Carr
Dept. of CE
Univ. of Michigan
Ann Arbor, MI 48104

Nr. Leonhard Bernold
School of CE
Georgia Inst. of Tech.
Atlanta, GA 30332

Prof. Jack Willenbrock
Dept. of CE
Penn State Univ.
University Park, PA 16802

Prof. Weston Hester
Dept. of CE
215 McLaughlin Hall
Univ. of Calif.
Berkeley, CA

Prof. Peter Lansley
University of Reading, Berkshire
P. 0. Box 219
Whiteknights, Reading
England RG6 2BU

Prof. Vir K. Handa
Dept. of CE
Univ. of Waterloo
Waterloo, Ontario, Canada
N2L 361

Mr. Diego Echeverry
Dept. of Civil Engineering
University of Illinois
Urbana, IL 61801

GROUP 4

Prof. D. R. Rehak
Dept. of Civil Engineering
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Mr. Gene Leach
Caterpillar Tractor Co.
100 N.E. Adams
Peoria, IL 61629

Prof. Dwight Sangrey
Dept. of CE
CMU
Schenley Park
Pittsburgh, PA 15213

Prof. Roozbeh Kangari
Dept. of CE
Geo. Inst. of Tech.
Atlanta, GA 30332

Prof. Abraham Warszawski
Dept. of Civil Engineering
Technion IIT
Technion City, Haifa
Israel

Prof. Photios Ioannou
322 West Engineering
University of Michigan
Ann Arbor, MI 48109

Mr. J. J. Kim
Dept. of Civil Engineering
University of Illinois
Urbana, IL 61801

Nr. Doug Wall
Dept. of Civil Engineering
University of Illinois
Urbana, IL 61801

AT LARGE

Dr. Gifford Albright
National Science Foundation
Construction Engineering and
Building Systems Program
Washington, D.C. 20550

Dr. L. R. Shaffer
USA-CERL
P. 0. Box 4005
Champaign, IL 61820

Professor C. William Ibbs, Jr. CONFERENCE LEADER
3140 Newmark CE Lab
University of Illinois
208 North Romine Street
Urbana, IL 61801

APPENDIX D

VARIOUS CONSTRUCTION SOFTWARE

EXHIBITED CONSTRUCTION SOFTWARE

Dan REHAK INSIGHT

Shallow Trench Soil Classification and Design Expert System

Determine soil classification (based on visual data), determine trench design parameters (shoring spacing, slope, etc.) and trench design for shallow excavation based on criteria developed by the National Bureau of Standards.

Geoffrey TRIMBLE SAVOIR
(1515 Redhill
Surrey, UK)

A System to select handling equipment (cranes and support equipment) for multi-storey construction.

Takes account of soil characteristics, nearby excavations, geometry of building, etc., under development. The shell has a database access facility and this vill be shortly be implemented.

B. PAULSON INSIGHT
(Stanford Simulation,
not ES)

Cyclone-based discrete operations simulator program with some graphics and interactive features.

- VIP - Videotape data acquisition program to control VCR while user builds tables of data, then does statistical conversion of data to standard distributions.
- INSITNET - Draws insight network.

L. BERNOLD MICROCYCLONE

Structured program for the simulation of construction processes which includes graphical input and output modules for increased user friendliness.

- Earthwork equipment optimization program with:
  - QTO
  - Earth Distribution
  - Equipment Database
  - Network Libraries and simulation modules

R. LEVITT — INSIGHT Knowledge System

Expert System Shell of IBM PC ($95.).

User friendly shell for building rule-based expert systems. Has ability to accept uncertain responses and combine uncertain evidence (limited).

Enter rules with word processor, compile them, and then consult knowledge bases with runtime version. Backward chaining, can select goals.

R. LEVITT

THE DECIDING FACTOR
Power Up Software
P. 0. Box 306
Half Moon Bay, CA 94019
(800) 851-2917

The ulitmate in user friendly expert system shells for the IBM PC ($95).

Uses problem decomposition, evidence – hypothesis framework; certainty factors and boolean logic excellent. Uses conditional logic to affirm/reject hypotheses based on out of range evidence (can be used as "go to" or pruning" function). Ideal for evaluation tasks; easily adapted to selection, prediction, interpretation. The best shell I have used for prototyping rule systems quickly and easily. Backward chaining with pruning "go to."

P. LANSLEY

AROUSAL
3 the Hollies
Wigginto, Tring.
Hertfordshire, UK
HP23 6EA
(044) 282-5980

A Real Organizational Unit Simulated as Life

A highly sophisticated business simulation system designed to assist contractors and other construction industry firms in developing their managers and in evaluating the potential costs and benefits of different business and organizational strategies. At the heart of the system is a case study of a real firm and a computer model of its business activities. Unlike many computer models which are restricted to handling financial, marketing and production issues, AROUSAL recognizes the vital interplay between strategic and operational decisions and the human side of business. AROUSAL is unique in being able to handle such factors as the design of the reporting structure, job descriptions, recruitment and general personnel issues. This ability is further enhanced by the flexibility of the system, which can be fine-tuned to reflect the activities and organization of a wide variety of businesses.

R. KANGARI

Fuzzy Set Analysis of Construction Risk

The main objective of this program is to estimate the uncertainty related to a construction project based on linguistic variables. The program can be used by project managers who cannot express their experience numerically. The model allows the user to define the decision element and objective function and describe the uncertainty related to a project by words. The program also estimates the variation of the decision element.

The program runs on IBM-PC. For more information contact R. Kangari, School of Civil Engineering, Georgia Institute of Technology, Atlanta, GA 30332; (404) 894-2296.