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A Structure for Construction Input During Preliminary Design

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A STRUCTURE FOR CONSTRUCTION INPUT DURING PRELIMINARY DESIGN

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ABSTRACT: This paper presents the results of a research project that focused on identifying and classifying the constructibility knowledge required during the programming, conceptual design, and schematic design phases of a complex building project. The investigation was a longitudinal study of the process of programming and early design for the Advanced Materials Research (AMR) Facility at Stanford University. The principal result of the investigation was the development of a structure for Constructibility Knowledge (CK). This structure led to the development of five testable hypotheses. These hypotheses were tested with direct interviews with key personnel of the project team. The results qualitatively validated the proposed structure. The conclusions of the paper highlight practical applications and describe potential areas for future research.

INTRODUCTION

The purpose of this paper is to present the results of a research project funded by the Center for Integrated Facility Engineering (CIFE) at Stanford University. This project focused on identifying and classifying the constructibility knowledge required during the programming, conceptual design, and schematic design phases of a complex building project. The investigation took advantage of an unusual opportunity for access to the process of programming and early design for the Advanced Materials Research (AMR) Facility, the first building of the Near West Campus redevelopment project at Stanford University. This longitudinal study provides new insights regarding constructibility input to key design decisions regarding the structural and mechanical systems of the project in these early design phases.

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The Center for Integrated Facility Engineering (CIFE)

The Center for Integrated Facility Engineering (CIFE) is a unique, cooperative venture at Stanford University [CIFE 1988]. A joint collaboration between the departments of Computer Science and Civil Engineering, the Center provides a particularly rich and diverse environment for researchers developing new computer-aided tools that address key problems in the A/E/C industry. Its mission is to develop computer-based tools and educational curricula that will encourage better integration of the facility engineering, construction, and management process.

CIFE has the unique opportunity of having a major project as an invaluable source of information and a testbed for prototype technologies developed through the Center's research. With particularly fortunate timing, the Center has been established just as Stanford's Near West Campus development project is getting under way. Over the next ten years, this project will provide an ideal, "real world" laboratory where researchers can study the total architecture, engineering, and construction processes and test their ideas. Stanford's Facilities Project Management Group has affirmed its intention to play an active role in CIFE research efforts. Access to such a unique testing ground is an invaluable resource for the Center.

Near West Campus Development Project (NWC)

The Near West Campus Development Project is a $250 million planning effort by Stanford University to develop the future science and engineering quadrangle adjacent to the main quadrangle on campus [TAC 1987a]. This region has approximately 41 acres of land composed of a mixture of obsolete and aging one- and two-story buildings with more modern three- and four-story buildings. The result of this effort will be an integrated neighborhood of outstandingly designed, functional and economic science and engineering facilities.

This redevelopment project brings challenges of unusual proportions: a wide spectrum of different, but almost simultaneous, academic needs; a whole region to work with, which contains numerous existing buildings, streets, and utilities located within a strictly controlled environment for design and construction; and an obligation to be innovative in function and aesthetic in expression.

Implementation of NWC will require extensive collaboration between all the parties involved. The final NWC Plan communicates two main concepts: the components of the plan and the design guidelines. The first defines the physical components that are the framework of the plan, while the second guides the implementation of basic planning principles and aesthetic character embodied in the plan [TAC 1987b]

A Reader's Guide

The first section of this paper gives a brief description of the project used as a test case for the investigation. The next section provides a brief background of the investigation describing the research scope, objectives, and methodology. A description of a proposed structure for constructibility knowledge follows. The next section reports the the hypotheses and principal findings of the investigation. The paper concludes with a description of the main insights from the investigation, practical applications and extensions of the findings, and additional research.

THE ADVANCED MATERIALS RESEARCH FACILITY (AMR)

The AMR project will house multidisciplinary materials research activities at Stanford University. It is a good example of the increased awareness and specific efforts by leading owner, design, and construction firms to integrate construction input early into the design process.

Project Description

The building has an expected total of 120,000 gross square feet (13,000 square meters) with 65,000 net square feet (7,000 square meters) of assignable space. The building breakdown is approximately 55% for laboratory space, 38% for office and seminar space, and 7% for support and storage. Special requirements include clean room space from Class 10 to Class 10,000, strict vibration control, a machine shop, and an electroplating shop. AMR is expected to be in active operation by Fall 1991. The overall budget is targeted at $32 million. The project is currently at the middle of schematic design.

The Project Team

AMR has an integrated design-construction team: owner, design, and construction teams are present from the initial phases of design of the facility. The *Owner Team* includes the Facilities Project Management (FPM) office at Stanford, who manage design and construction for all Stanford projects, and the members of members of AMRAC, an Advisory Committee appointed by the university to advise the deans involved in the project. The other two members of the integrated project team are: the *Design Team*, Anderson DeBartolo Pan (ADP), Inc., Architecture & Engineering, Tucson, Arizona; and the *Construction Team*, Kitchell Contractors, from Irvine, California. They both have extensive experience in this type of project and have worked together in several projects before. Both have contracts with the owner. External participants having jurisdiction over the project include the Building and Health Departments, and the Fire Protection District of Santa Clara County, Bay Area Air Quality Control District, and the Stanford University Health and Safety Department.

BACKGROUND OF THE INVESTIGATION

The overall research approach for the study involved identifying early design decisions, specifically related to the structural and mechanical systems of the project, that generate a need for constructibility input; describing a structure for this input; testing hypotheses concerning decisions and types of constructibility knowledge for input; describing the process of constructibility input and the mechanisms used in the AMR project; and developing findings and generalizations concerning constructibility knowledge requirements for the preliminary design of buildings.

Research Objectives

The following five objectives focused the research tasks: 1) identify programming, conceptual design, and schematic design decisions for the structural and mechanical building systems, which generate a need for constructibility knowledge to assist in the Analysis-Generation-Evaluation-Selection processes; 2) identify and classify the types of constructibility knowledge that are necessary for specific programming and early design decisions; 3) describe the process and mechanisms for capturing and providing constructibility knowledge in an example project (AMR); 4) collect additional data for quantifying benefits of design-construction integration; and 5) provide a basis for future research to develop knowledge bases for design-construction integration.

Research Scope

The scope of this investigation contained three main elements: 1) it focuses exclusively on the AMR project and principally on the programming and conceptual design phases of the project, with a secondary focus on the schematic design phase; 2) interviews included only individuals directly involved in the project (project management personnel of the Owner Team; the principal architectural, structural and mechanical designers of the Design Team; and the project management personnel and senior estimator of the Construction Team); and 3) the study focused on construction input and construction-related issues.

Research Methodology

The principal components of the methodology followed in this investigation were to:

- *Extract relevant findings from previous background literature reviews*. These included programming and design processes, constructibility, construction methods, knowledge structures, and all related topics.
- *Identify design decisions that require constructibility input*. The main thrust of this activity was to develop hypotheses about constructibility knowledge input to specific design

decisions as we investigated the AMR project. These hypothesis were based on Vanegas' model for design-construction integration [Vanegas 1987] and other background constructibility research and literature [Bryson 1984; CII 1987; CTF 1987; O'Connor et al. 1986; O'Connor & Tucker 1983 and 1986; Tatum et al. 1985 and 1986]. The specific design decisions selected for the study were the results of an analysis of the AMR project.

- *Investigate the Advanced Materials Research Project.* This included background, scope, current program, and current design activities. The principal activities were 1) to observe and document principal project team meetings, 2) interview the key personnel in the owner, the design, and the construction management teams, and 3) analyze any available documentation.
- *Analyze the Data.* The data included identifying:
  - For the Programming Phase, space requirements, types of spaces, and other elements of defining the facility requirements that can benefit from constructibility knowledge.
  - For the Block Diagramming Phase, constructibility knowledge requirements for design decisions regarding the structural system and the mechanical system.
  - During the Schematic Design Phase, constructibility knowledge requirements for design decisions regarding the structural system and the mechanical system, including specific configuration decisions that would provide many needs for constructibility knowledge, and influences on construction methods and installation sequence that are likely considerations in constructibility input to schematic design.
- *Report the Results.* The deliverable product of this investigation was a technical report submitted to CIFE.

A STRUCTURE FOR CONSTRUCTIBILITY KNOWLEDGE (CK) REQUIREMENTS

An appropriate structure for CK is needed to better understand the role and the characteristics of this knowledge in the design process. This is achieved by describing: 1) how CK initially supports programming and is an integral part of conceptual and schematic design; and 2) its contrasting characteristics. A better understanding of CK is essential for the development of computer and non-computer based tools for design/construction integration.

This section gives a description of the proposed structure: a descriptive model that provides a conceptual framework for CK. Because the model is primarily descriptive, managers can adapt it to specific company and project needs. The structure allows the development of systems to capture and disseminate this knowledge. It highlights issues that, if overlooked, may preclude from benefitting from early construction input.

The Role of Constructibility Knowledge

As shown in Figure 1, CK supports the two basic functions of preliminary design: problem seeking and problem solving. Although closely related, these two concepts are very different and have special characteristics that affect CK.

Insert Fig. 1 about here.

For problem seeking, CK assists programmers in asking the questions and in identifying the key issues that will have an impact on construction in two ways: 1) for the project design parameters; and 2) for the principal project components. For these two, three key global areas initially emerge as the main leverage points for construction input: definition of cost parameters; definition of schedule parameters, and definition of building systems and construction methods that support form and function considerations. Each one of these, even in advance of the design, has the potential to generate specific construction-related issues or concerns that need to be addressed by the design solution.

For problem solving, on the other hand, CK provides designers with direct construction information that supports three basic concepts: 1) the level of detail of the design solution determines the specific type of CK required; 2) CK contributes to decision-making; and 3) CK enhances the *analysis* (i.e., understanding the problem); *generation* (i.e., providing alternatives); *evaluation* (i.e., comparing alternatives); and *selection* (i.e., choosing alternatives) process. These three ideas will be discussed in more detail later.

Constructibility Knowledge During Programming

CK is necessary for a better and more complete definition of the project at the programming stage in two ways, as shown in Figure 2. Programming is the first step in the design process; it defines the problem. Its basic goal is problem-seeking, answering four basic questions [Peña et al. 1977]: 1) what does the client want to achieve and why (*Goals*); 2) what is the project all about, i.e., data describing existing project conditions such as physical, climatic, regulatory, and aesthetic aspects (*Facts*); 3) how many spatial and environmental requirements exist, such as the purpose and function of each space, spatial relationships between them, and occupancy, environmental, safety and quality requirements (*Needs*); and 4) how does the client want to achieve the goals (*Concepts*). Finally, programming also identifies the basic *Issues*, which designers must address in achieving a design solution to the given problem. In short, programming outlines the design concepts that will allow designing a project that meets its goals, satisfying its needs and working with the facts. It does not offer a design solution; it states a very specific problem. This stage contains no design decisions. Decisions are limited to those that create boundaries and parameters that will later guide the design efforts.

Insert Fig. 2 about here.

These five global categories form the set of project design parameters. They present a problem because they are often intangible, not easily quantifiable, or subjective in nature. For example, flexibility may be a goal. The question becomes: what is flexibility? How can you measure flexibility? How does flexibility translate into specific design solutions? Another example is a functional need for closeness between two given spaces. The question becomes: how close is close? Can you measure closeness? An example of a fact is the existence of codes and ordinances. The question becomes: what is the correct interpretation of the norm? Are there ways to "bend" the norm? Finally, people assign different priorities to these ideas. For some, facts drive a project; for others, it may be the concepts or the goals.

But identifying these five types of parameters in a project is not enough; it is necessary to organize a basic structure for query to be able to relate them to specific components of the project. All components of a project fall in four main areas: 1)*Function*, which refers to the people who will use the facility, the activities performed by them, and how the two relate; 2)*Form*, which refers to all information generated concerning the project's site, environment, and desired quality levels of all spaces of the facility; 3)*Economy*, which refers to the initial budget, the operating costs, and the lifecycle costs of the facility; and 4)*Time*, which refers to all considerations regarding the past, present, and future of the facility and the pressures for fast completion of construction.

The organization in these four categories forms the set of project components. They are more tangible in nature than the design parameters, making it is easier to visualize a functional relation between several spaces; discuss formal elements that will affect a project like site constraints; and analyze the estimate and schedule for the project.

This structured approach for programming creates a matrix that organizes the constraints and guiding parameters for design of a project. Each one of the cells in the matrix can contain both general and specific questions regarding constructibility. CK allows asking the proper questions. Rather than restricting "creative" design, it complements and enhances the design solutions for a project. Without this knowledge, programmers stating a problem may overlook important considerations that may have a strong impact on construction or even in ultimate project performance.

CK highlights construction implications. Every project is unique and it is impossible to develop a universal checklist. What is important is to develop a set of global implications for construction. These need to be tailored to the specific nature and context of each project. Possible categories include: resource availability, complexity of project, resource management, design criteria, and project context. These categories will be discussed in more detail in a later section.

All the information that is generated at this stage is then used to assist designers during the next stage of the process, conceptual and schematic design. CK also plays an important role there. This is described next.

Constructibility Knowledge During Conceptual and Schematic Design

A basic premise, as shown in Figure 3, is that CK is an integral part of the design efforts. It is not possible to design without thinking how that design can be built. Thus, CK enhances and supports problem-solving during conceptual and schematic design, but because the design process is such a complex system, CK has to fit both vertically and horizontally. This means that through iterative cycles of problem-solving, it progresses through increasing levels of detail and complexity, and at the same time gets involved in numerous decisions at different milestones of the process.

Insert Fig. 3 about here.

Vertical Integration.- The different levels of the design solution require different types of CK. This is *vertical integration.* It occurs over time and is important because it assures that the outputs of each of the design phases are consistent.

The conceptual design phase produces the proposed conceptual solution, which establishes the overall site layout, the main relationships between the spaces that form the project (e.g., adjacencies, organization, grouping), principal accesses and circulation schemes, general volumetric forms, renderings, and definition of basic systems. The output from the schematic design phase has a higher level of detail. It produces a preliminary solution that, at this level, is more formal. Schematic design generally includes scaled drawings of floor plans, sections, perspectives, a more detailed definition of building systems, and the establishment of general specifications. Subsequent phases continue the development of design to ultimately end in a total coordinated set of construction drawings, specifications, and details.

CK must parallel the evolution of the design solution through the different design phases and adjust to the different levels of detail of the outputs at each phase. Once again, the basic leverage points are: definition of cost parameters; definition of schedule parameters, and definition of building systems and construction methods.

Horizontal Integration.- Horizontal integration occurs in several ways: 1) in the owner's team users and special consultants work together as a single unit; 2) all the design disciplines act as a single unit to produce a single product, a building design; 3) in the construction team the different sources of construction input such as vendors, specialty subcontractors, or other consultants work together as a single unit; and 4) the owner team, the design team, and the construction team form the project team.

In addition, a completed project is the single product of a series of parallel subprocesses. From an initial program, two sets of parallel activities develop. The first is the architectural design of the project; the second is the technical design of the project, which, in turn, can be broken down into individual supporting engineering design disciplines. These parallel processes come together for a decision whether to continue with the next design phase or continue developing the specific design solution. CK must assist in making decisions at the different design phases and at specific milestones of the overall process.

Analysis/Generation/Evaluation/Selection (AGES).- The problem of tailoring CK to the different requirements of the design process can be further observed by applying the AGES model, originally developed by Hickling [1982]. This model assumes that any design problem can be broken down into parts.

In the AGES process, there are four stages of inquiry: 1) what is this problem all about? 2) what are the different ways of looking at it? 3) which of them describe the problem well? and 4) can we choose one to help us get a grip on the problem? The result is a solution for the original problem. It is a dynamic and iterative process that may or may not be sequential: the analysis can start at any of the four questions and continue any of the paths highlighted by the arrows. The process described applies to the activities of both design and construction input.

This framework may seem an over-simplification of a very complex problem, but it appears to fit the way both design and construction input function. A special situation stands out, at every stage of the process, the individual alternatives cannot stand alone or be isolated from the rest: they have to be seen in an overall context. This generates the largest challenge for CK: how to support, in a dynamic way, all the different permutations that arise from the AGES process taken as a whole.

Characteristics of Constructibility Knowledge

So far, the structure has addressed the general role played by CK in programming and preliminary design activities. This section analyzes in more detail the special characteristics of this knowledge, shown in Figure 4. Too often, people tend to generalize and refer to construction input as a single concept. They have the perception that this knowledge is homogeneous and that anyone from construction can provide it. This is a misconception.

Insert Fig. 4 about here.

First, the implications of CK are not the same at all times. The range of implications includes cost and schedule issues, design performance, and construction methods. Second, there are different types of CK. The knowledge about the overall performance of a mechanical system differs from the knowledge of the specific details for a vibration control table for the equipment. Third, CK comes from different sources ranging from very detailed engineering analyses to "gut-feelings" based on many years of experience. Finally, the mechanisms for data-collection, AGES of design alternatives, and communication of CK vary greatly. These four characteristics are discussed next.

Implications.- CK provides information for design decisions that has three distinct types of implications: cost and schedule implications; technical considerations that affect design; and methods considerations that affect construction.

In the first type of implication, CK assists designers in developing a solution within given cost and schedule parameters. This is the main reason why owners get construction involved early in the project: to obtain accurate cost and schedule estimates. However, in a similar manner to the

CK classification discussed above, estimates can be of different types depending on the level of definition of the design solution and the criteria used for grouping the various cost components of a facility. However, a problem with current estimating approaches, specially in the early phases of design, is that they lack substantiation and documentation to explain the basis for the cost figures. Many cost estimates are based on historical data with little attention given to communicating the supporting information to the other party. For example, a cost per square foot figure alone does not mean anything; it has to be based on many specific assumptions. The range goes from global to detailed line items. The smallest elements combine into higher levels until a single figure is reached. However, in passing from one level of detail to the next, valuable information is, many times, lost.

Another approach, *systems estimating*, is important for designers. The unit of analysis is the total system with all of its components. While a global estimate establishes a general cost boundary, systems estimating provides ranges in which architects can move to obtain a design solution that meets the established budget. Individual systems cost become moving targets that combine with each other until a balanced total is achieved.

A third approach, *space planning estimates*, is also important to designers, but the unit of analysis is the space itself. Here, cost boundaries are given in terms of the types of spaces included in the program of the facility. Individual systems cost are broken down by space and included within the unit cost of area of the given space. Combinations of individual types of spaces and the respective associated costs become moving targets that combine with each other until a balanced total is achieved.

One drawback with estimating during these early design phases is that constructibility issues do not surface easily in this approach. An interesting alternative is to attach construction thinking to the estimating process in a more direct and evident way. This can be referred to as *methods estimating*. Methods estimating requires that all cost figures be associated with a specific way of building, a method.

The second type of implication of CK, technical considerations that affect design, support the design function. The role of CK is to provide input that assists in developing design solutions that allow construction efficiency. Theory not always translates into reality. CK supports that transition from a construction point of view, based on direct experience in the fabrication, installation, and use of materials in a given system.

Finally, CK highlights methods considerations that affect construction. These fall in five categories:

- *resource availability*: are there any constraints due to a lack of labor, materials, or equipment? Is there enough space for storage or construction operations? Do we have enough energy to support construction operations? Do we have technologies to support specific project objectives? Is there enough time for construction?
- *complexity of the project*: does the project have any special requirements for labor skills, construction methods, or technologies?
- *resource management*: does the project have conditions that will influence labor (e.g., training, jurisdiction, interference, or agreements)? Does the project have special procurement considerations? What contractual implications exist? What approach is needed for work packaging?
- *design criteria*: what governing criteria exist (e.g., architectural landmark, optimization, aesthetics, etc.)? Are there desires to standardize? What are the construction implications of material selection?
- *project context*: Are there any special site, weather, or climate considerations? How restrictive is the working environment? Have all applicable norms, regulations, and codes been identified?

Types.- CK has two main types: general and specific. *General knowledge* deals in concepts; *specific knowledge* deals in details. Every project goes through increasing levels of detail and CK must be tailored to each. This implies that the type of knowledge required at the beginning is different from that required at the end of the design process. However, they are closely related and complement each other. General knowledge requires support from specific knowledge and specific knowledge requires general knowledge to maintain the focus on a given problem.

The wrong type of CK at a given level of solution brings more problems than benefits to the design process. Focusing too fast on details may cause frustration among architects who want to establish a concept before going into details. Conversely, providing general ideas when detailed thinking is required does not contribute to the quality of design.

Sources.- CK requires different sources, also tied to the evolution of design. At the program level, the basic source is a broad experience base. Nothing can replace the knowledge gained by doing something directly. Years of experience develop heuristics, "gut-feelings," and other special skills in managers of construction. But this generalist ability is not enough. The complexity of projects today requires people who are well-informed and willing to learn new things. As the project enters into conceptual design, the source of CK becomes a combination of experience and a strong technical base. This requires a combination of a generalist and specialist approach.

Schematic design requires a solid technical base. CK is obtained through research and extensive analyses of specific problems. This is a specialist approach. From this point on, CK supports design from detailed specific knowledge, complete definition, extensive coordination, and thorough review.

Mechanisms.- The interactions between people in a project are of diverse nature. This also translates into different ways to collect and communicate CK. The first mechanism refers to how a firm operates within itself (i.e., internally based on company policies or established procedures) and with other firms (i.e., externally based on jointly developed guidelines).

A second type of mechanism refers to group versus individuals interactions. For example, during programming, the programmers bring together all the people who have the authority, qualifications, knowledge, and capacity to answer these questions, through a series of established and formal communication processes. Some of the most common techniques used are: brainstorming, charrettes, and squatters. All have one thing in common: they bring people together and prompt them, under the direction of a specialist, to define all the project information that will influence design. This process is iterative and varies in duration depending on the complexity of the project and the number of people providing input. This contrasts with the individual approach where a person has little contact with his/her peers.

A third mechanism distinguishes between formal and informal mechanisms. Mail, memos, tele-records, transmittals, and electronic mail printouts between parties, agendas, minutes, handouts, and notes in meetings, and the program and all documents related to the budget, schedule, and contract administration of the planning and design process are the most common formal mechanisms of communication between parties. In addition, topics such as soils, health and safety, EIR, and other feasibility studies, merit special reports. All these leave a trace or documentation trail. Informal mechanisms, on the other hand, do not leave trace, although this does not preclude a contribution based on individual comments.

FINDINGS

Based on the structure for CK discussed previously, the researchers developed a set of testable hypothesis to serve as the basis for the questionnaire used in the interviews. Specific hypotheses explore specific components of the structure, while the general hypothesis establishes the overall validation of the structure.

Specific Hypotheses:

- *CK has two different roles during preliminary design: a) Problem-Seeking (During Programming); and b) Problem-Solving (During Design).*
- *CK supports two distinct processes during programming (problem-seeking) in identifying construction implications (i.e., resource availability, complexity of project, resource management, design criteria, and project context) for: a) goals, needs, facts, concepts, and issues (project design parameters); and b) function, form, economy, and time (principal project components).*
- *CK forms an integral part of conceptual and schematic design (problem-solving) in three ways: a) it parallels the design process providing input at each project phase at the appropriate level of detail (vertical integration): b) it assists in making design decisions at specific milestones in the design process (horizontal integration); and c) it enhances the process of Analysis-Generation-Selection-Evaluation of design alternatives.*
- *The four principal characteristics of CK are: a) CK contains three different types of implications (i.e., cost and schedule, technical considerations that affect design, and methods considerations that affect construction); b) there are different types of CK (i.e., general vs. specific); c) CK has different sources (i.e., experience vs. analysis); and d) it requires different mechanisms (i.e., formal vs. informal) for data-collection, Analysis-Generation-Selection-Evaluation of design alternatives, and communication.*

General Hypothesis:

- *The structure for CK during the preliminary design phase can be summarized by the following: 1) CK has two different roles during preliminary design; 2) CK supports two distinct processes during programming; 3) CK forms an integral part of conceptual and schematic design in three ways; and 4) CK has four principal types of characteristics.*

In general, the structure was well received. There was no strong disagreement with the hypotheses. We believe that the data collected through the interviews support well our hypotheses. This validation is not quantitative, but rather, it is qualitative.

Specific Examples of Constructibility Knowledge

Examples of CK can be grouped into several categories: architectural, site constraints, structural system requirements, and mechanical system requirements. It is very difficult to isolate

CK from other types of knowledge during these early phases. All the project team contributed in incorporating CK to the design. The following examples were obtained in the interviews.

During Programming.- Construction concerns in this phase were mostly the cost impact that programming decisions were going to have on the project, and schedule implications of certain programmatic decisions. However, they also included functional issues concerning spaces, specially those stemming from the implications of handling toxic materials in the laboratories (occupancy requirements of UBC Code: H-6); the strict vibration requirements of the facility with the corresponding structural ramifications; flexibility requirements of the facility; site constraints; and the given parameters of the NWC plan. These issues are analyzed and documented [ADP 1988].

During this phase, there was little involvement of the structural and mechanical disciplines. The only key issues related to these disciplines were defining the module size for laboratories and determining the structural grid for the building.

Other specific examples of programmatic considerations are:

- *resource availability.*- This included the concrete formwork system. Forms to meet the original dimensions were only available in other cities and at a high cost. As a result, dimensions on the slab span module were modified accordingly. The tight site also led to reduced mobility and the potential use of tower crane instead of a crawler type.
- *resource management.*- Several concepts were considered such as the EIR report that can become a critical path item and delay the start of construction; equipment that can be retrofitted from the old labs to the new; and utilities that may become a "can of worms," whether they are moved or built around.
- *complexity of the project.*- The structural requirements imposed by loading, vibration and seismic conditions, and the toxic waste handling made this a very complex project and became the primary forces behind the design of the facility. This is related to another consideration: the use of service corridors instead of interstitial space.
- *design criteria.*- . The design criteria were strongly influenced by existing guidelines established by the NWC plan, H-6 requirements, and aesthetics and massing considerations, and also by ADP's approach to projects, design process (e.g., squatters), and experience.

  Originally, the criteria was steel, but then it changed to concrete. Construction input has identified that the site is not big enough for easy handling of concrete, disposal of soil, and that a single supplier of concrete would have difficulties satisfying the quantities required by the magnitude and schedule of the facility. This has had no immediate effects so far, since the project still has not been totally defined schamnetically yet.

- *project context.*- This context provided interesting challenges because 1) Stanford has very strict parameters that govern design and construction of new facilities and a complex structure for decision-making, and 2) there are many agencies involved in the process of issuing permits, monitoring, and control of these types of facilities.

During Conceptual Design.- During block diagramming construction input provided ideas regarding construction methods, specifically: the evaluation of different structural systems (e.g., consideration of using a combination of a steel structure for office spaces with a concrete structure for the laboratory spaces) and the overall configuration of other building systems. These analyses considered cost, performance, and "design appropriateness." The analysis, in cost and also in constructibility, of what it meant to obtain different levels of vibration limitation with different structures was of special importance.

The specific input of Kitchell during conceptual design focused on estimates of the different schemes developed by ADP. During block diagramming (i.e., conceptual design), construction was active, principally "keeping a thumb on the budget." They have provided coordination of the process, assisting consultants and estimators to keep on schedule. They provided 20 estimates including value engineering of different alternatives.

Other specific construction input included many areas: roof type (changing from concrete to steel); arcade; matrix of materials; analysis for structure systems, equipment; detailed skin analysis; cost and schedule impacts; impacts on future NWC developments (removal of the power station); and utility corridors.

During Schematic Design.- Here, construction input was similar to conceptual design but at a greater level of detail, focusing on more specific building components, and refining all the previous areas. Construction input continued with value engineering of skylights, glazing, clean room modules, and realistic local budgets for electrical, mechanical systems.

The contribution of construction input to design decisions in this phase included input for the configuration of the building; determination that the roof did not require the same type of structure as the intermediate floors; evaluation of form availability for specific structural dimensions; consideration of steel frame for the office areas of the project (abandoned later); study of windows and skin alternatives; analysis of site considerations such as accessibility; and scheduling of the overall process including relocation of existing elements and demolition.

Other examples of construction input to conceptual design include extensive analysis of materials for the roof and skin; design of the arcade; effect of seasons on construction operations; familiarity with local bidding climate; active participation in contacting agencies for the interpretation of codes; plans to deal with a small and tight site; and the need for shoring and underpinning.

CONCLUSIONS

Insights from the Investigation

The following three aspects highlight the importance of identifying constructibility knowledge requirements for the preliminary design of buildings:

1) *Increased the understanding of vertical integration:* The horizontal and vertical interdependencies between all components of an integrated project are complex. Furthermore, decisions made during the initial phases of design have a larger impact on the project than decisions made later in the process.

   Thus, attention to the design-construction interface during the initial phases of design is vital for effective vertical integration, not only for the outcome of the project, but also for the development of better tools to support integration. The structure for CK developed in this investigation reinforces these concepts.

2) *Assistance in overcomming prior limits of constructibility research:* Prior constructibility research studies reached a limit because of the lack of understanding of knowledge requirements [Bryson 1984; O'Connor et al. 1986; O'Connor & Tucker 1983 and 1986; Tatum et al. 1985 and 1986].

   An initial structure of constructibility knowledge requirements allows better matching of construction personnel and the type of construction input to the different design phases. In addition, understanding these requirements helps capture useful and relevant post-construction information for future projects.

3) *A structure for constructibility input that benefits all phases of the project:* A fundamental structure for constructibility knowledge was needed. Another limitation of previous efforts to study constructibility has been the fragmentation of the overall process and the fact that construction input commonly is the result of specific project needs and problems.

Understanding the structure and characteristics of CK supports planning for appropriate mechanisms of construction input. This integration will eliminate fragmentation by incorporating construction as an integral part of design.

Early involvement not only allows better initial decisions, but also helps anticipate problems during construction, which allows preventive rather than corrective actions.

Practical Applications and Additional Research

This investigation has opened several possibilities for practical applications and further research. In some ways, it has only touched on the tip of an iceberg. In others, it has provided a solid base to begin building actual tools for integration.

Practical Applications.- An immediate application of this structure is the development of an organized construction input system with guidelines and procedures. Documentation of the design process is a concern for many projects. If there was an independent procedure that would capture and organize all the construction-related issues, without increasing the work load of the project team members, it would enhance the quality of design. Many good ideas are currently lost due to lack of documentation. This structure for CK can help establish historical databases of construction issues.

This structure also consolidates the participation of construction during the design process, beyond the simple estimating and scheduling role. Managers from owners can use the structure as a guideline to make best use of construction input. Designers can realize that the structure does not alter their design processes. What it does is clarify how construction input fits and benefits the design process.

Additional Research.- An initial objective that could not be fulfilled by this research still merits further study: what are the quantifiable benefits of integration? How can we measure them?

But beyond the scope of this investigation, the next step is to continue expanding the CK structure to encompass all design phases. Design development and contract documents have characteristics that make them different to schematic and conceptual design. Another longitudinal study would complement the findings of this investigation.

The next extension goes into construction operations. The question that arises is: what is the structure of CK during construction? In order to better provide input during design, how can we capture and organize lessons from projects? What are the important issues that need to be incorporated into the design?

Finally, with this structure as a base, can we develop a constructibility knowledge base system that would assist designers during the initial phases of design of a building project? As a starting point, programming offers an ideal area of investigation to do this. Previous attempts have been limited in scope. A better way would be to develop a system for the CK structure that can accommodate any project, serving as a master template.

Much progress has been made in understanding processes that until not too long ago were beyond the scope of construction. This is only the beginning, but additional efforts in these areas will not only continue to support CIFE efforts, but also contribute to increased performance of the A/E/C industry.

ACKOWLEDGMENTS

This investigation was funded by the Structures and Buillding Systems Program in the Division of MEchanics, Structures, and Materials Engineering of the National Science Foundation under Grant M5M-85-52727 and by the Center for Integrated Facility Engineering. This support is gratefully acknowledged. The authors also wish to acknowledge the collaboration of the people from the different companies that compose the project team, who allowed us to impose on their busy schedules and who shared with us their experiences in a candid and open way.

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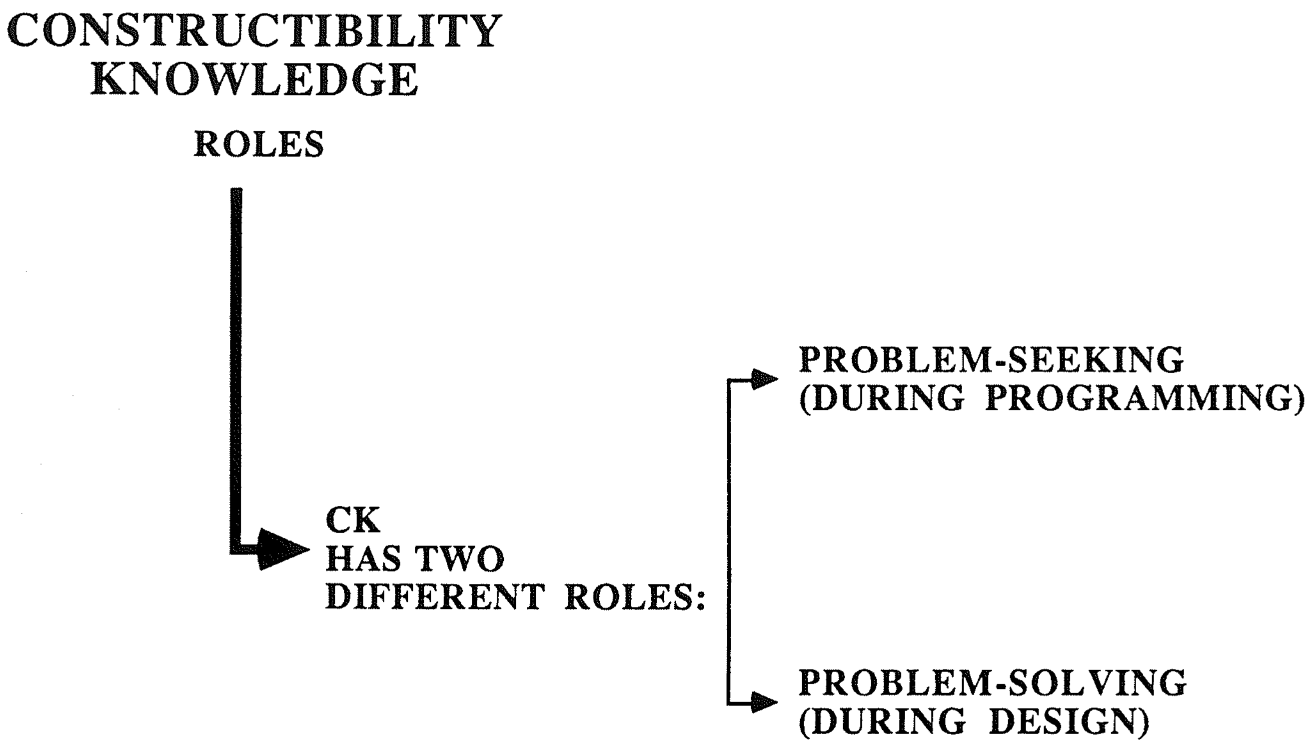

Fig. 1.-- Constructibility Knowledge Roles

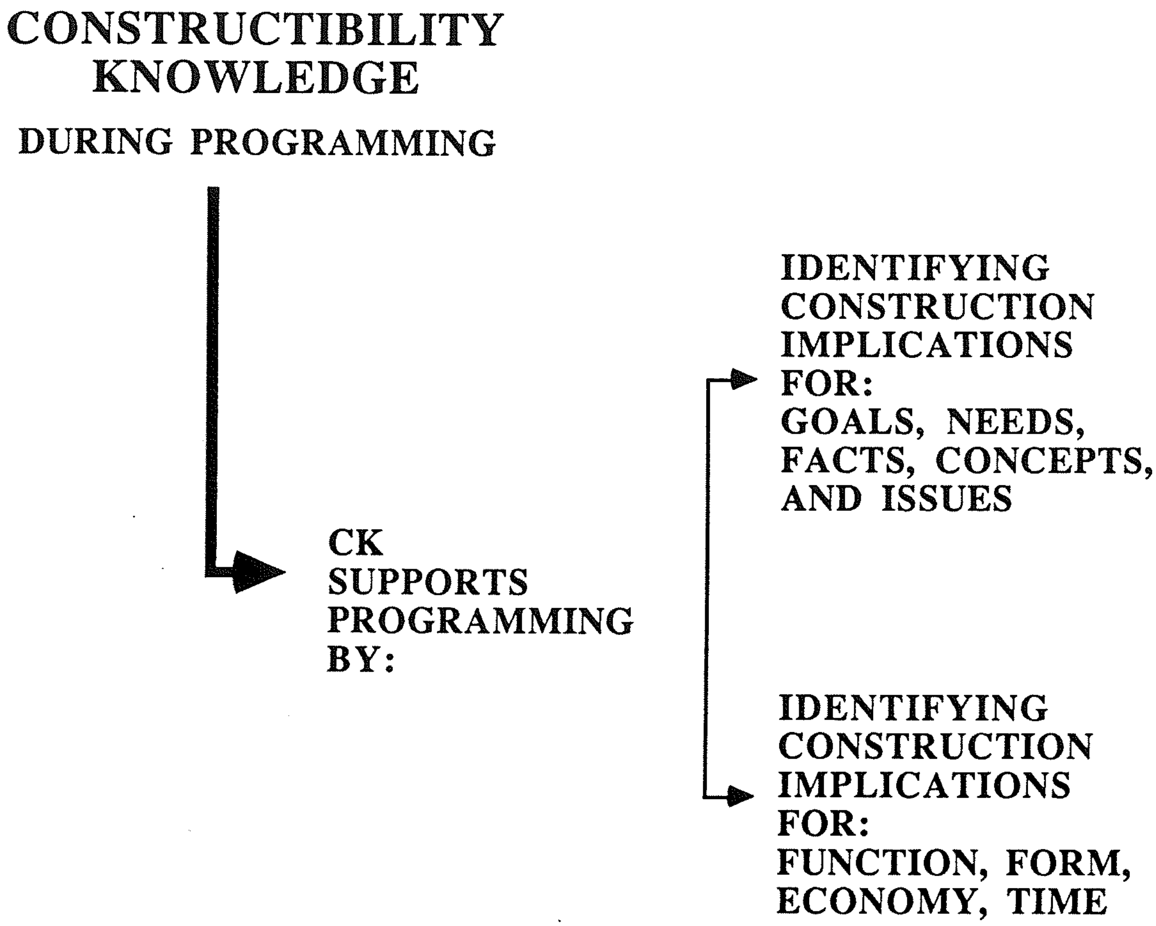

Fig. 2.-- Constructibility Knowledge During Programming

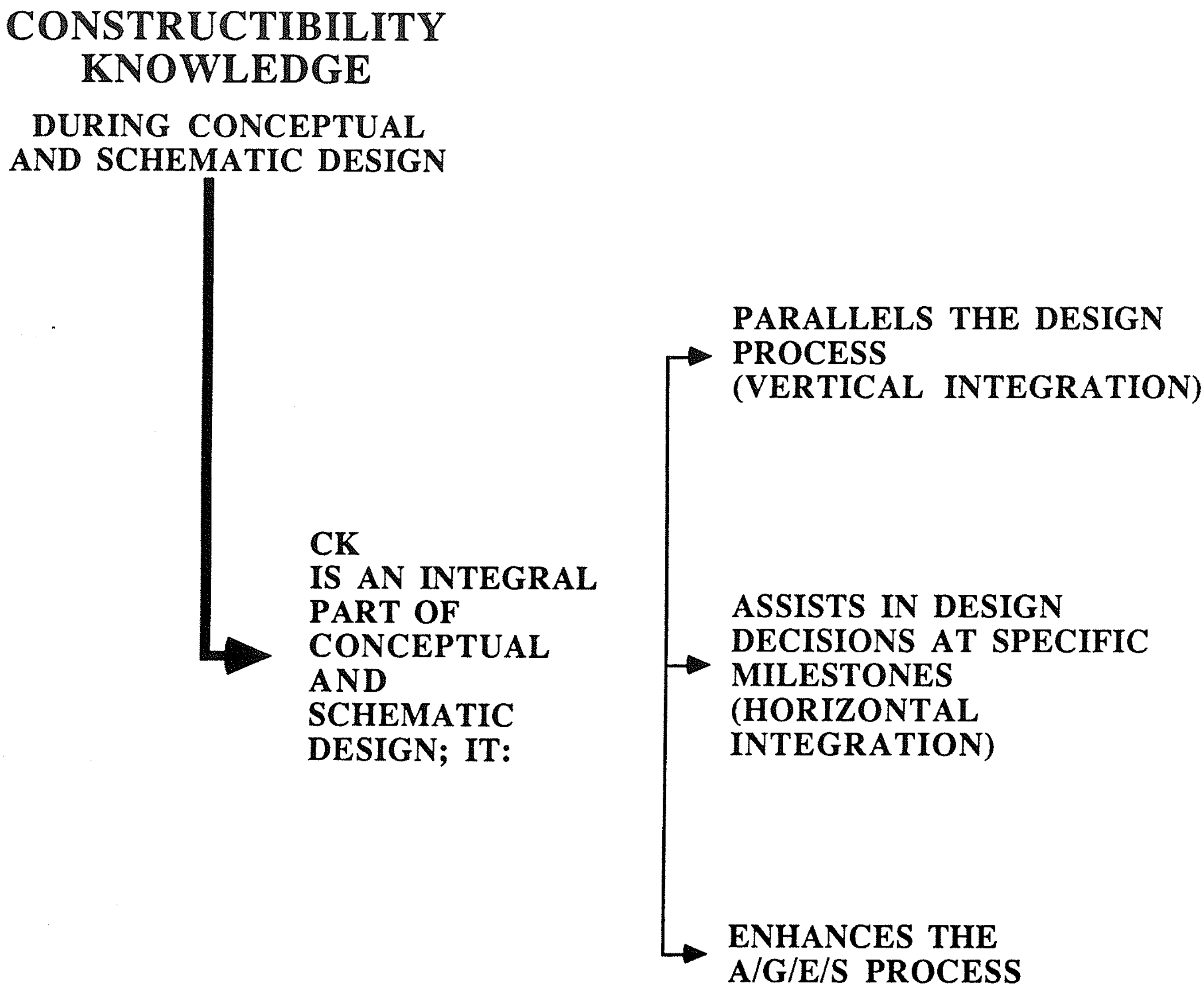

Fig. 3.-- Constructibility Knowledge During Conceptual and Schematic Design

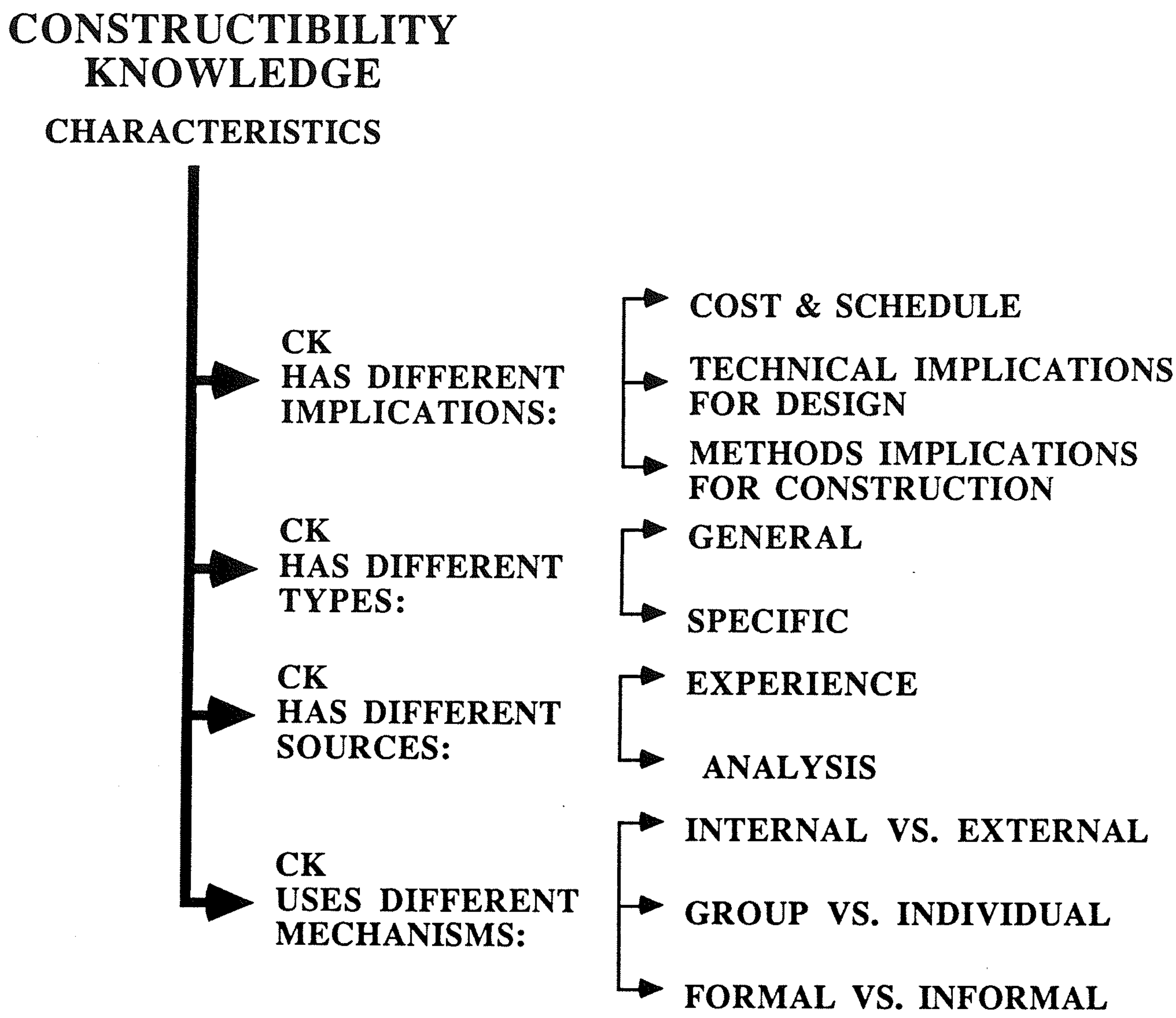

Fig. 4.-- Characteristics of Constructibility Knowledge

A STRUCTURE FOR CONSTRUCTION INPUT DURING PRELIMINARY DESIGN

By Jorge A. Vanegas, C. B. Tatum, and Vince Colarelli

RETAIL SALES SUMMARY:

This paper is about several related subjects: integration of construction input to the design process; a structure for construction input during the initial phases of design; the role of constructibility knowledge; constructibility knowledge requirements during programming; constructibility knowledge requirements during conceptual, and schematic design; and the characteristics of constructibility knowledge. The paper presents the findings of longitudinal study of the preliminary design process of a complex laboratory project, with a focus on structural and mechanical design issues.

KEY WORDS:

Architectural Design

Construction Input

Constructibility

Knowledge

Programming

Structural Design

Conceptual Design

Construction*

Integration

Mechanical Design

Schematic Design

* included in ASCE's list of key words

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