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THE EFFECTS OF CONSTRUCTION KNOWLEDGE ON THE AUTOMATION OF PRELIMINARY BUILDING DESIGN

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ABSTRACT

This paper presents an approach to providing an automated decision support system for Preliminary Building Design. It integrates knowledge from different domains, mainly from construction, using Knowledge Based Expert Systems methodology. Given the overall geometric parameters for the building, this approach explicitly incorporates construction knowledge about major building components such as Foundations and Structure, Mechanical and Electrical, Envelope and Roof, and Building Finishings into the early phases of the design decision-making process. An example of its use is presented in the preliminary design of a low-rise commercial building. It is implemented on a mainframe computer using the Design Specialist and Plans Language (DSPL) developed by one of the authors.

INTRODUCTION

Decisions made at the early stages of project development have a major impact on the final cost of a constructed facility, as well as on operating and maintaining the building through its economic life.

In a restricted environment, constrained by tight schedules, limited budgets, owner subjective preferences and sometimes vaguely defined objectives, the designer must effectively integrate knowledge and information from domains of diverse nature and origin, such as real estate marketing, engineering and architecture, and building technology and regulations. The decision-making process at this stage is highly complex and ill-structured, depending heavily on the designer's expertise and professional judgement.

Preliminary design decisions must give consideration not only to the long-term implications of the finished building performance such as operability, maintainability, marketability, strength and serviceability but also to short-term implications such as the ease of construction or constructability. Timely consideration of construction related issues are of special importance since construction cost is a significant part of the total cost of the building.

CONSTRUCTABILITY DURING PRELIMINARY BUILDING DESIGN

The concern for cost and schedule-effectiveness in the construction industry has directed attention to project constructability.

Constructability is considered to be the optimum integration of construction knowledge and experience in planning, engineering, procurement, and field operations to achieve overall project objectives (1). This concept emphasizes "buildability" or the ability to construct. It also emphasizes the importance of construction input to all project phases.

The major implication of constructability is its integrating effect on all phases of project development. This property has been widely recognized by the industry.

This integrating effect is mainly the result of organizational commitment to the constructability concept. This commitment makes it easier to overcome contractual, technical, and operational barriers that limit the amount of construction input given during early project phases. A team of specialist working together plays a major role in the implementation of successful constructability programs. Construction input is given by a consulting expert who is available to the designers. Professional Construction Management and Design-Build are typical project organizations that demonstrate this concept.

When there is no direct organizational support for constructability input or reviews, the integration of this knowledge into design depends heavily on the designer's prior construction experience. However, this expertise can now be made available through an automated decision support system which provides the designer with timely and correct information.

AUTOMATION OF INTEGRATED DESIGN

Advances in the computer technology had contributed to the automation of portions of engineering design. In civil engineering projects, CAD and Word Processing systems have greatly contributed as productivity tools for the production of project documents, such as plans and specifications.

In recent years, Knowledge-Based Expert System (KBES) methodology has been explored as a way of developing systems to assist designers in the selection and use of information and hueristic knowledge during design decision-making. These efforts have been primarily directed towards understanding the implications of KBES methodology in specific areas of design, such as structural applications (2), (3), (4). Initiatives are underway to develop more integrated approaches for design (5).

The model presented here attempts to automate an integrated approach for the preliminary design of buildings.

The integration of design and construction knowledge begins by identifying small pieces of both types of knowledge that are directly complementary, such as in design steps, where the constructability knowledge provides immediate assistance to the design decision-making process. For example, certain types of bolted connections for the structure should be avoided because the currently available bolts are imported from a country that has been shipping low quality bolts. Therefore, if they are used, the connections will fail the field inspection, and redesign of those connections will cause delays and additional costs.

The specific issues that arise from the integration of design and construction knowledge differ between firms and individuals, depending on many variables, such as the organization, individual idiosyncracies, and individual or group experiences. The underlying core knowledge, however, is basically the same.

Recent studies (6), (7) have identified major constructability concepts, and have attempted to categorized them. These include the execution of the project plan, site layout, construction methods, simplification, standarization, modularity and preassembly, and adverse weather. These concepts have a direct impact on the design process itself and on the constructability of design.

Figure 1 shows a conceptual view of how automation methodologies support different approaches for integrating construction knowledge into design. A high level of integration of both knowledges is achieved when constructability knowledge is fragmented in many pieces and each piece is made timely available to assist the corresponding design step. This approach truly integrates the two types of knowledge. it is used by design experts with extensive construction experience. Alternatively, this experience can be systematically encoded and implemented on a computer using KBES methodology as it is done in the work presented here and represented in the upper left portion of the figure.

At the other extreme, lower right portion of the figure, a situation not uncommon to many construction projects is represented. Faulty designs, from the construction point of view, are constantly modified through change orders and rework as the building is assembled. The construction input in these cases is given too late. Computers are used more to document changes than to positively influence the design

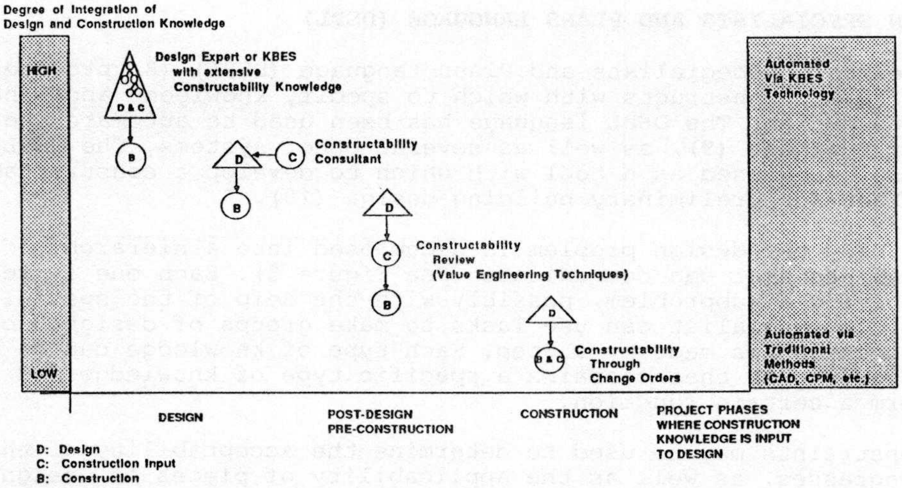

Figure 1. Automation of Integrated Design and Construction Knowledge

The potential benefits of a highly integrated and automated approach are conceptually shown in Figure 2. As the level of integrated knowledge increases, the amount of time that it takes to produce the design is reduced since the automated environment assists the designer in identifying only constructable alternatives. In addition, the number of required changes is reduced. As a consequence, it can be expected that more constructable designs lead to lower costs and shorter construction times.

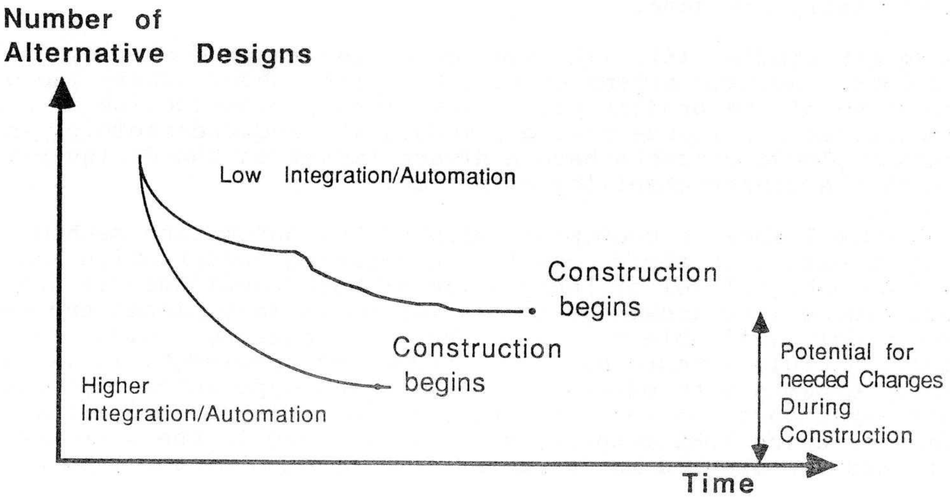

Figure 2. Expected Benefits of
Increased Integration and Automation of Design

DESIGN SPECIALISTS AND PLANS LANGUAGE (DSPL)

The Design Specialists and Plans Language (DSPL) (8) provides a number of different constructs with which to specify knowledge about how to do a routine design. The DSPL language has been used to automate the design of an Air Cylinder (9), as well as several other systems. The DSPL language is also being used as a tool with which to develop a constructability assistant for preliminary building design (10).

In DSPL the design problem is decomposed into a hierarchy of Specialists that can communicate (See Figure 3). Each one is responsible for solving a subproblem, possibly with the help of the specialists below. A specialist can use Tasks to make groups of design decisions. Each decision is made by a Step. Each type of knowledge can be viewed as an active agent that contains a specific type of knowledge and can perform a certain function.

Constraints may be used to determine the acceptability of the design as it progresses, as well as the applicability of pieces of design knowledge, and the compatibility of subproblem solutions. The methods of solving a subproblem are stored as Plans in the appropriate specialist. A knowledge-based plan selection mechanism using Sponsor and Selector agents is available. Failing constraints can trigger a form of dependency directed backtracking which is controlled by Failure Handler and Redesigner agents.

Constructability knowledge is primarily used in constraints, sponsors, and selectors, but it can be used by a step when making a single decision as the example presented in the following section. If necessary, the language can be extended to include other forms of constructability analysis.

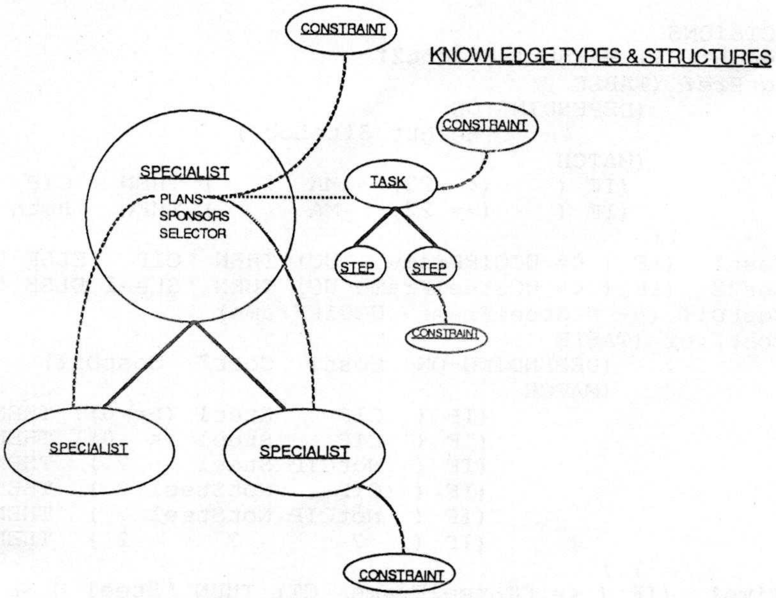

Figure 3. Knowledge Types and Structures
in the Design Specialist and Plans Language (DSPL)

DSPL is flexible enough to allows users to express design knowledge for their specific needs, according to their organizational idiosyncrasies and experience. The DSPL Acquirer (Knowledge Acquisition Component) permits users of DSPL to enter design knowledge without having to concentrate on the details of its syntax.

The system consists of the Designer plus a collection of data-bases (See Figure 4). The Designer contains both design knowledge and constructability knowledge. The organizational principle is problem decomposition. Different parts of the Designer solve different design subproblems. They can be thought of as active agents, containing structured procedural knowledge. As subproblems themselves may have subproblems, the system allows some agents of the Designer to use other agents to help with their responsibilities.

In routine preliminary designs (11), possible solutions are known in advance, and subproblems interactions are essentially eliminated. This can be achieved by checking for possible difficulties during the solution of the first subproblem of a potentially interacting pair. The few interactions that may remain are handled by Constraints.

Design results are stored in the Design Data Base (DDB). The requirements for the design are stored there too. Other data bases are used for information, such as costs, that can be stored in tabular form. The DDB and the other data bases can be accessed by all of the agents during design. This allows prior design decisions to be available for use during the solution of other design subproblems.

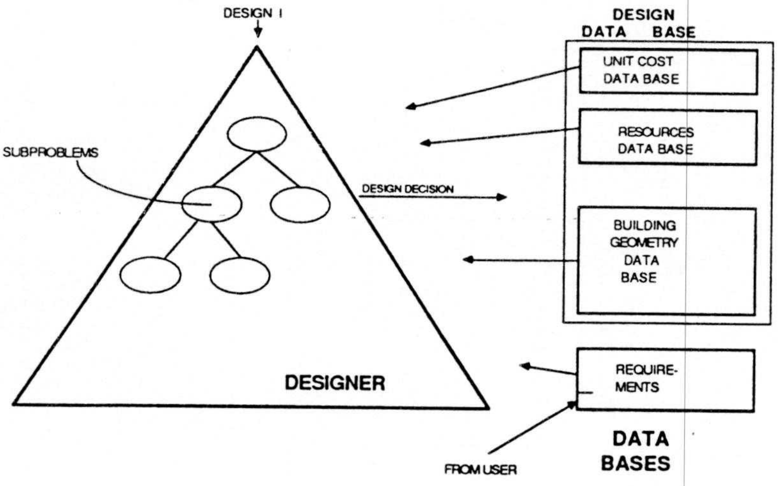

Figure 4. System Structure

EXAMPLE

To illustrate the components and operation of the the model a group of design agents implemented in DSPL are presented. In this portion of the preliminary design process the structural frame of a two-story office building is selected.

The building is hypothetically located in Central Massachusetts. It is to be an above average quality office structure. The building is to have a gross floor area of approximately 14000 square feet divided into two office floors. It is expected however, that only 85 to 90 percent of the total gross floor area will be leasable space. Construction is expected to start in the early spring and to be completed within 10 months. The owner has allocated a budget of no more than $75.00 per square foot for the construction of the building.

General information about the building, the site, as well as the designer's structural material preferences are stored in the Requirements Database. General information about cost of resources, material properties, and building codes are previously stored in the Design database which will also store information about the building as the design takes place.

The Designer consists of a top Specialist that interacts with the user and controls the entire preliminary process. Before proceeding with the preliminary design, the top specialist verifies that the architectural parameters building-height and floor-area meet the building code requirements. Failure to meet these constraints causes design failure. Architectural input parameters must be reviewed and defined to a code acceptable level before design continues.

At the next level down, the design effort is handled by three Specialists depending on the number of floors in the building. Design approaches are different since the effects of gravity and lateral loads on the structure are a function of building height which also has an effect on the selection of construction methods and equipment.

A group of Specialists responsible for preliminary design of the major

```
(SPECIALIST
 (NAME Structural)
 (USED-BY USER)
 (USES None)
 (DESIGN-PLANS  StructuralPlan1 StructuralPlan2)
 (INITIAL-CONSTRAINTS None)
 (FINAL-CONSTRAINTS None)
)
(PLAN
 (NAME StructuralPlan1)
 (TYPE Design)
 (USED-BY Structural)
 (BODY FrameChoiceTask1
        (REPORT-ON Frame)
       FloorChoiceTask1
        (REPORT-ON Floor)
       FoundationChoiceTask1
        (REPORT-ON Foundation)
))
(PLAN
 (NAME StructuralPlan2)
 (TYPE Design)
 (USED-BY Structural)
 (BODY FoundationChoiceTask2
        (REPORT-ON Foundation)
       FrameChoiceTask2
        (REPORT-ON Frame)
       FloorChoiceTask2
        (REPORT-ON Floor)
))
(TASK
 (NAME FrameChoiceTask1)
 (USED-BY StructuralPlan1)
 (BODY FrameChoiceStep1)
)
(TASK
 (NAME FloorChoiceTask1)
 (USED-BY StructuralPlan1)
 (BODY FloorChoiceStep1)
)
(TASK
 (NAME FoundationChoiceTask1)
 (USED-BY StructuralPlan1)
 (BODY FoundationChoiceStep1)
)
(STEP
 (NAME FrameChoiceStep1)
 (USED-BY FrameChoiceTask1)
 (BODY
  (KNOWN
    Height1        (KB-FETCH 'Requirements 'BuildHeight1)
    Height2        (KB-FETCH 'Requirements 'BuildHeight2)
    RPref          (KB-FETCH 'Requirements 'RegionPreference)
    SiteLoc        (KB-FETCH 'Requirements 'SiteLocation)
    UCSteelFrame   (KB-FETCH 'Frame 'UnitCostSteel)
    UCCIPFrame     (KB-FETCH 'Frame 'UnitCostCIP)
    CTSteelFrame   (KB-FETCH 'Frame 'ConstructionTimeSteelFrame)
```

Figure 5. DSPL Design Step for
Selection of Structural Frame

```
   CTCIPFrame     (KB-FETCH 'Frame 'ConstructionTimeCIPFrame)
   UC             (KB-FETCH 'Requirements 'UnitCost)
   CT             (KB-FETCH 'Requirements 'ConstructionTime)
  )
  (DECISIONS
   Height   (+ Height1 Height2)
   HgtPref (TABLE
             (DEPENDING-ON
                        Height SiteLoc )
             (MATCH
              (IF (     (<  22)    MA       ) THEN   CIP     )
              (IF (     (>= 22)    MA       ) THEN   Both    )
          ))
   Cost1  (IF ( <= UCCIPFrame   UC) THEN 'CIP   ELSE 'NotCIP)
   Cost2  (IF ( <= UCSteelFrame UC) THEN 'Steel ELSE 'NotSteel)
   CostDif ( - UCSteelFrame  UCCIPFrame)
   CostPref (TABLE
               (DEPENDING-ON  Cost1  Cost2  CostDif)
               (MATCH
                       (IF (  CIP    Steel (>= 0)) THEN  CIP  )
                       (IF (  CIP    Steel (<  0)) THEN  Steel)
                       (IF (  NotCIP Steel    ? )  THEN  Steel)
                       (IF (  CIP    NotSteel ? )  THEN  CIP  )
                       (IF (  NotCIP NotSteel ? )  THEN  None)
                       (IF (   ?        ?     ? )  THEN  None)
            ) )
   Time1  (IF ( <= CTSteelFrame  CT) THEN 'Steel ELSE 'NotSteel)
   Time2  (IF ( <= CTCIPFrame    CT) THEN 'CIP   ELSE 'NotCIP)
   TimeDif ( - CTSteelFrame CTCIPFrame)
   CTPref  (TABLE
             (DEPENDING-ON   Time1  Time2  TimeDif)
             (MATCH
                       (IF (  Steel    CIP   (>= 0)) THEN  CIP  )
                       (IF (  Steel    CIP   (<  0)) THEN  CIP  )
                       (IF (  Steel    NotCIP   ? )  THEN  Steel)
                       (IF (  NotSteel CIP      ? )  THEN  CIP  )
                       (IF (  NotSteel NotCIP   ? )  THEN  None)
                       (IF (   ?        ?       ? )  THEN  None)
            ) )
   REPLY   (IF (EQ CostPref 'None) THEN (FAILURE))
   REPLY   (IF (EQ HgtPref 'None)  THEN (FAILURE))
   Final  (TABLE
           (DEPENDING-ON
                  HgtPref CostPrf RPref CTPref)
           (MATCH
            (IF (  Both    CIP      ?      CIP   ) THEN  CIP )
            (IF (  Both    CIP    Steel    CIP   ) THEN  CIP )
            (IF (  Both    CIP    Steel   Steel  ) THEN Steel)
            (IF (  Both   Steel    CIP     CIP   ) THEN  CIP )
            (IF (  Both   Steel    CIP    Steel  ) THEN Steel)
            (IF (  Both   Steel     ?     Steel  ) THEN Steel)
            (IF (  CIP      ?       ?       ?    ) THEN  CIP )
            (IF (   ?       ?       ?       ?    ) THEN None )
           )
           (OTHERWISE None)
         )
  REPLY (IF (EQ Final 'None) THEN (FAILURE))
  REPLY (KB-STORE 'Frame 'FrameChoice Final)
)))
```

Figure 5. DSPL Design Step for
Selection of Structural Frame (Continued)

building components, that is, Structural, Roof and Enclosure, Mechanical, Electrical and Heating, Ventilating and Air Conditioning (HVAC) assist the process one level below.

Figure 5 shows the DSPL code for the Structural Specialist and the agents that support it in the selection of type of structural frame, floor system, and type of foundation for the building. Each of these decisions is made by individual Tasks and Steps. The process continues by using a lower level Specialist that controls the preliminary sizing of the members, that is, columns, girders, joists, slabs, etc..

The Step shown in Figure 5 represents the decision point of the structural Task of selecting the frame. Constructability concerns such as construction time, building codes and predominant construction methods for the region have been directly integrated in the decision-making process. In DSPL, a variable/expression pair represents an assignment of the value of the expression to the variable.

In the example, two potential structural frames are compared on the basis of floor height, construction cost, construction time, and predominant material used in the area.

The floor height is a determinant factor to establish the type of mechanical, electrical, HVAC and fire protection systems. Horizontal and vertical space that is available for the installation of these systems is of prime consideration for the selection of the structural frame. The trade-off between cost and construction time may be extremely important for the profitability of the investment. The predominant type of construction in the region is a proxy for construction related factors such as labor type (union/non-union), labor availability, construction methods, material suppliers, etc..

The final matching table shows the explicit simultaneous consideration of these factors. A qualitative assessment of the impact of these factors on the selection of the structural frame is made. The table could be constructed differently depending on the designer's views and the particular project objectives and constraints.

In a similar fashion, construction knowledge can be incorporated in other design Steps. It could also be incorporated into design Plans and Specialists to influence the way in which the design is conducted.

CONCLUSIONS

The KBES methodology is appropriate to support automation of integrated design and construction knowledge which is otherwise available only through experts.

High integration of design and construction knowledge can be accomplished by making avaliable small pieces of relevant constructability knowledge at each design step. Construction information and knowledge leading to constructability improvements can be generally categorized but the specifics are different in each case.

The DSPL language allows explicit representation of construction knowledge at each design step. It also provides a flexible environment to accomodate different idiosyncrasies and project circumstances to implement an automated decision support system for preliminary building design.

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