INTEGRATED CAD/KBS APPROACH FOR AUTOMATING PRECONSTRUCTION ACTIVITIES

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ABSTRACT: Preconstruction activities include design analysis, cost estimating, and value engineering. They are performed to provide clients with the data to make intelligent and informed decisions about constructing their facilities. Cost plays an important part in preconstruction activities; owners want to know accurate construction costs up front to determine if they meet their budget. Various design alternatives need to be considered and compared with respect to cost, performance, and reliability and the best one selected to achieve the ultimate goal of the project. However, often because of the time restraints of preconstruction activities, the number of design alternatives considered is limited. The lack of time is one reason unnecessary cost gets into the design. The effectiveness of preconstruction activities can be improved by expediting the generation of design alternatives and improving the accuracy of their cost estimates. This can be achieved through the integration of knowledge-based systems and computer-aided design systems. This paper discusses such an integration and describes an application developed for the preconstruction analysis of mezzanine structures. Preconstruction analysis of mezzanine is an integrated knowledge-based computer-aided design system that captures structural design knowledge and cost information and enables sales personnel, without engineering background, to produce accurate preliminary designs, realistic price quotations, and detailed layout drawings.

INTRODUCTION

Preconstruction activities that include design analysis, cost estimating, and value engineering (VE) provide potential owners with the benefit of early analysis of the effects that materials, equipment systems, techniques, and schedules will have on project time and cost. These activities allow the owner and the design team to make the best decisions before construction begins, with the result of reducing the overall construction costs. The importance of preconstruction activities has increased during the past few years. One reason for this increase is rising construction, operation, and maintenance cost of facilities. Another reason is the growing popularity of the design/build project delivery system, which requires a project price and scope of work to be guaranteed to the client prior to producing final drawings and completing engineering design work.

Preconstruction activities are resource intensive and require the combined efforts of professionals from different disciplines. Some of the biggest challenges in performing preconstruction activities are the development of accurate preliminary cost estimates and the development and comparison of alternative designs.

Development of Accurate Preliminary Cost Estimates

Preliminary cost estimates play an important part in preconstruction activities; owners want to know accurate construction costs up front to determine if they meet their budget. If estimated costs are more than expected, the project usually is redesigned to reduce the costs. Accurate preliminary cost estimates also are important for performing VE studies. The VE studies are performed on the basis of cost and if poor cost information is used, the basis for VE evaluation is hampered (Dell'Isola 1982). The preliminary estimate should include all potential costs and quantities to allow the owner to make informed decisions early when it has the most benefit.

From the foregoing discussion, it is clear that the importance and accuracy of the preliminary cost estimate cannot be overstated. Yet, the estimates made at the preliminary stages of the project usually are conceptual in nature and usually are calculated in terms of a given set of design parameters such as square footage, cubic footage, and/or footprint area. Statistics show that cost estimates calculated this way can vary from a mean of 29% to a maximum of 66% from actual cost (Parker and Dell'Isola 1991).

Development and Comparison of Alternative Designs

There are a multitude of combinations of design, materials, and methods that can be used to achieve the ultimate goal of a project. The optimal design should include the best balance between cost, performance, and reliability and is determined by performing VE analysis. The VE is a proven management technique used to identify alternative design approaches for satisfying the requirements of the project while lowering costs and ensuring technical competence in performance. The goal of a VE study is to achieve true value for the owner. The value may come in the form of removing unnecessary costs to the project, or it may come in the form of providing a more workable product that would decrease the costs of owning and operating the facility. The VE analysis usually looks at the cost of various design alternatives that can be used to achieve the ultimate goal of the project. The number of alternatives considered in arriving at a final design greatly influences the cost of a project. The alternatives are compared with respect to cost, performance and reliability, and the best one is selected. Often, because of the time restraints of the design schedule and budget, the number of design alternatives considered is limited. The lack of time is one reason unnecessary cost gets into the design (Zimmerman and Hart 1982).

The foregoing discussion illustrates that the effectiveness of preconstruction activities can be improved by expediting the generation of design alternatives and improving the accuracy of their cost estimates. This can be achieved through the integration of knowledge-based systems (KBSs) and computer-aided design (CAD) systems. Such integration would capture design knowledge and cost information into the knowledge base and enables the generation of several design alternatives whose parameters can be imported automatically into CAD to produce drawings. The speed of design is increased dramati-

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cally and the quality of cost estimates is improved allowing more design alternatives to be compared for achieving optimum value.

An application that applies knowledge-based linked CAD techniques for the preconstruction analysis of mezzanines (PAM) was developed (Tabatabai-Gargari 1993). The PAM is used to perform preliminary structural design, conduct automatic quantity takeoff of materials, estimate cost based on actual quantities, and automatically generate drawings. The system supports different local codes of practice and can handle various loading requirements. The design parameters are extracted automatically from the results of the knowledge-based consultation and input into CAD to produce drawings with exact dimensions. The integration of knowledge-based and CAD permits the rapid development of several design alternatives that can be compared to select the least expensive. The system does not only increase the speed of preliminary design but more accurately determines member loads and actual dimensions of structural elements. The cost estimates used in the preconstruction analysis are thus improved because they are based on actual quantities.

INTEGRATION OF KBSs AND CAD SYSTEMS

A KBS, also called expert system, is a computer program that emulates the problem-solving process used by human experts. A KBS contains the knowledge, experience, and judgment of experts and is well suited to solving problems where judgment and experience play an important role (Bell and Elzarka 1992). A wide range of KBS applications have been developed in the construction industry. Applications have been developed to assist with such diverse tasks as document drafting, claims resolution, crane rigging, pipe welding, and roof inspection. A KBS can be developed as either a stand-alone application or as an integrated system where it is linked to CAD software and database-management systems. When linked to CAD, a KBS has a tremendous potential for automating the design process.

The CAD has been used widely in the construction industry. However, its use has been limited to drafting for so many years that it is sometimes referred to as computer-aided drafting. The CAD has much more potential than just automating the drafting process. The CAD database contains a vast amount of information that can be utilized in ways that intelligently help many of the parties involved in the construction process (Reinschmidt and Finn 1990). For example, geometrical information contained in the CAD database can be used to check "intelligently" design against existing specifications by examining dimensions and cross sections of structural members. The geometrical information also can be used to deduce scheduling relationships (Morad and Beliveau 1991). If the geometrical database is augmented by other information such as material type, cost, expected life, aesthetic value, etc., the CAD system can be utilized to perform VE analysis as described in this paper.

An intelligent CAD system as described earlier requires the integration of CAD systems with database-management systems and KBSs. Such integration is becoming more and more feasible with the constant increase of power and capability of commercially available software products. The integration of KBS with CAD is of extreme importance when automating preconstruction activities because it frees the user from an overwhelming data entry load (Levitt 1990). By integrating KBS with CAD, the KBS can interrogate automatically the CAD database for any required information and the recommendations of the KBS can be inserted automatically into the CAD model.

AUTOMATING PRECONSTRUCTION ANALYSIS OF MEZZANINE STRUCTURES

Mezzanines are steel structures, normally prefabricated, which are used widely inside warehouses for better utilization of space. Their lightweight, ease of construction and fast erection make them ideal for providing additional office and/or storage spaces.

The nature and characteristics of the mezzanine industry make it ideal for automating its preconstruction activities. Mezzanine projects usually are design/build. In a design/build contract, the owner enters into an agreement with a single firm to produce all planning, design, and construction with its own in-house capabilities. The principal advantages of design/build contracts are the elimination of contractor claims against the owner resulting from errors in the plans or specifications and the ability to begin construction on each separate phase of the project as its design is completed. Improving the effectiveness of preconstruction activities is extremely important in design/build projects because the project price and scope of work usually need to be guaranteed to the client prior to the final drawings and engineering design work. Also, to increase their chance of getting the project, design/build contractors need to demonstrate to potential owners the value that they bring to the project through VE and constructability analysis. In the past, design/build was more predominant in the private sector and almost always was associated with standard warehouse and manufacturing facilities. Today, it is being used more and more by governmental agencies for construction of various types of facilities. The growing popularity of design/build projects have emphasized the importance of preconstruction activities. Because these activities are usually labor intensive and knowledge intensive, they are good candidates for automation.

There are other factors that make the mezzanine preconstruction activities a good candidate for automation. Mezza-

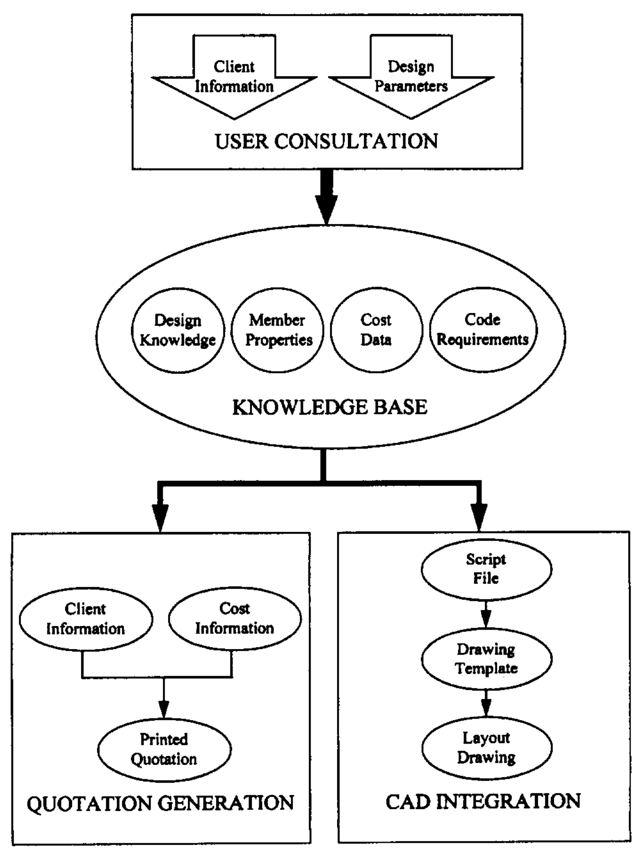

FIG. 1. Integrated Model for Automating Preconstruction Activities

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nines are used for various purposes and their structural design is subject to a wide range of loading requirements. The mezzanine manufacturing industry is global in its nature; manufacturers work with customers from all over the world and have to meet different local code requirements. Also, mezzanine structures have to fit inside existing buildings without interfering with existing facilities. What adds to the complexity of the preconstruction activities is that time is extremely important to the customer, and, hence, speeding the process of producing an accurate estimate and performing a sound VE analysis is a key competitive factor.

SYSTEM DESCRIPTION

The PAM is an integrated knowledge-based CAD system that was developed to perform preliminary structural analysis and design and develop accurate cost estimates that are used to perform VE analysis of mezzanines structures. It interfaces with commercially available CAD software. As illustrated in Fig. 1, the knowledge base is the central repository of all structural design knowledge and is developed in Pascal. It contains the information required to support the activities of structural design, cost estimating, and drawing generation. The design knowledge is based on various codes including the Building Officials and Code Administrators International and the Occupational Safety and Health Administration that the user can select from. The knowledge base contains information on code requirements and on properties of structural steel members such as cross-sectional area, moment of inertia, section modulus, etc. This data can be tailored to the manufacturers operations and needs. The system is capable of performing the structural design of columns, beams, and joists of the structure using American Institute of Steel Construction and Canadian Institute of Steel Construction specifications.

The knowledge in PAM is modeled in the form of production rules that are expressed in an IF-THEN format. Non/design data such as the client name, address, phone number, and contact person are entered during the knowledge-base consultation. An example of PAM consultation is illustrated in Fig. 2. At the end of the consultation, a client-specified quotation report is produced. The report contains information on maximum member sizes, quantities, and properties of auxiliary members (e.g., stairs, hand rails, gates, etc.) and maximum column loads. Maximum column loads are important to verify the suitability of existing floor slabs for supporting loads. If the slab is not strong enough, isolated footings are required. The user can specify the language of the report. Currently, two languages are supported: English and French. An example of a quotation report is illustrated in Fig. 3. The report contains the technical specification of the mezzanine as well as its cost.

The cost estimate produced by PAM utilizes a unit price database and actual design quantities. Once the consultation is completed, the knowledge base automatically calculates required steel weight and cost based on the designed length,

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CONSULTATION SESSION

Enter quotation # >		001
Enter Customer's Name >		Edgar Allen
Enter Customer's Company >		Material Handling Co.
Enter Customer's Fax No. >		1231231234
How many spans >		5
How many spaces >		4
Are all spans equal? Y, N >		N
Enter (feet) Span 1 >		19.5
Enter (feet) Span 2 >		16.0
Enter (feet) Span 3 >		14.25
Enter (feet) Span 4 >		18.00
Enter (feet) Span 5 >		21.75
Enter (feet) Space 1 >		7.5
Enter (feet) Space 2 >		16.75
Enter (feet) Space 3 >		19.25
Enter (feet) Space 4 >		10.00
Enter max joist spacing in inches >		39
Enter Structure height in feet >		10.25
Knee brace (1 if standard), (0 if none) >		1
How many stair cases ? >		1
Exterior or interior ? E, I >		E
How many landing ? >		1
How many ladders ? >		1
How many feet of handrail ? >		250
How many feet of kickplate ? >		250
How many swing gates ? >		1
How many lift out gates ? >		1
Type of Deck ? (Steel deck and plywood	1,	
Bargrating	2,	
Steel deck and diamond plate	3,	
Open steel plank	4,	
No Deck	5) >	4
Enter OSHA or BOCA code >		BOCA
Enter live load (psf) >		120
Language of report ? (French Canadian	CF,	
English Canadian	CE,	
United States	US) >	US
Do you want to change anything ? Y, N >		N

FIG. 2. A PAM Consultation Session

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COMPUTERIZED MEZZANINE QUOTE #001

ATTN.:	Edgar Allen	CUSTOMER:	Material Handling Co.
FAX NO.:	1231231234		
ADDRESS:	1234 Green Avenue Somecity OH 45123		
QUOTE NO.:	001	Date:	1/3/1998

We want to thank you for choosing CAS. We are happy to respond to your request for a quote on one of our products. These documents contain a drawing of product as well as the specification and cost. We hope that this information will be sufficient in helping you to make your decision, but feel free to call us anytime for further details.

MEZZANINE SPECIFICATIONS:

SIZE:	89.50x53.50	SQ FOOTAGE:	4788.25
STRUCTURE HEIGHT, FT:	10.25	CLEAR HEIGHT, FT:	8.92
MAX BEAM SIZE:	16"	MAX JOIST SIZE:	14"
MAXIMUM COLUMN SIZE:	7"x7"	MAXIMUM COLUMN LOAD, LBS	49000
MAXIMUM BASEPLATE SIZE:	12"x12"	CODE:	BOCA
STD 36" WIDE STAIRCASE:	EXTERNAL, QTY: 1	STD LADDER:	1
STD 4'x4' LANDING QTY:	1	SWING GATE QTY:	1
LIFT-OUT GATE QTY:	1	HANDRAIL (LINEAR FEET) :	250.00
KICKPLATE (LINEAR FEET) :	250.00		

CAPACITY: 120 PSF, BASED ON UNIFORMLY DISTRIBUTED LOAD

- STD. STRUCTURE COLORS: GREEN___ BLUE x ORANGE___
- HANDRAILS ARE ALWAYS PAINTED "YELLOW"
- KICKPLATES ARE PAINTED THE SAME AS THE STRUCTURE
- MEZZANINES ARE DESIGNED IN ACCORDANCE WITH BOTH STANDARD.
- ALL CONNECTIONS USE ASTM A325 BOLTS.

CAS is always striving to make our dealers the most competitive in the market place. Now you can take advantage of our new lower prices.

Structure	Price: $45678.02
Galvanized Open Steel Planking	Price: $17561.81
Sub total	Price: $63239.83
Freight charges delivered to your address:	Price: $2345.67
Net 30 days	Total: $65585.50

Quotation will remain effective for 30 days We appreciate the opportunity of submitting this quote for your review

FIG. 3. A PAM-Generated Quotation

cross-sectional area, and unit weight of structural members (i.e., beams, joists, columns). The PAM also estimates connections between structural members (i.e., joist to beams, beams to columns, and joist to columns) and computes the number of required bolts, their weights, and cost. The cost of the deck and accessories such as stairs, handrails, ladders, and gates are estimated based on user specifications and unit costs. Shipping and handling is added to the cost of the structure to calculate the total quoted price.

The integration with CAD enables the transfer of design parameters from the knowledge base, such as location, size, and length of structural members, to AutoCAD to produce layout drawings, which can be viewed on screen or printed out. The graphical link to the design data is provided through the use of script files generation by the KBS after the user completes the consultation session. The script files reflecting design constraints are then called from within an AutoCAD template containing prestored details of columns, beams, base plates, etc. These details are scaled automatically and placed according to the design parameters. An example layout drawing is illustrated in Fig. 4.

The PAM has simplified the VE process of mezzanine structures. By increasing design speed and improving the quality of cost estimates, PAM allows more design alternatives to be compared for achieving optimum value. The PAM runs on a Pentium personal computer. The personal computer was chosen because of its widespread use and relatively low cost. To illustrate the advantages of automating preconstruction activities, selected PAM capabilities are examined.

Accurate Preliminary Cost Estimate and Price Quotation

Currently, most price quotations and preliminary designs of mezzanine structures are prepared by sales personnel rather than engineers. They rely on approximate guidelines and square footage prices. The resulting preliminary design is not accurate and is only approximate. The inaccuracy of design might result in many potential problems such as inaccurate price quotations and possibility of interference with existing facilities. However, the cost estimate produced by PAM is accurate because it is based on true dimensions and cross-sectional areas obtained from the structural design.

Drawing Production

The integration with CAD allows the early generation of layout drawings. The drawings are complete enough to describe accurately column and beam types and length, joist spacing, clearances, size of base plates, and maximum loading transferred to the floor. Such information is important to the customer to ensure that the mezzanine structure will indeed fit in his designated space without causing any interference or imposing excessive loads to the floor slab. Once drawings are completed they are faxed immediately to the client to be used

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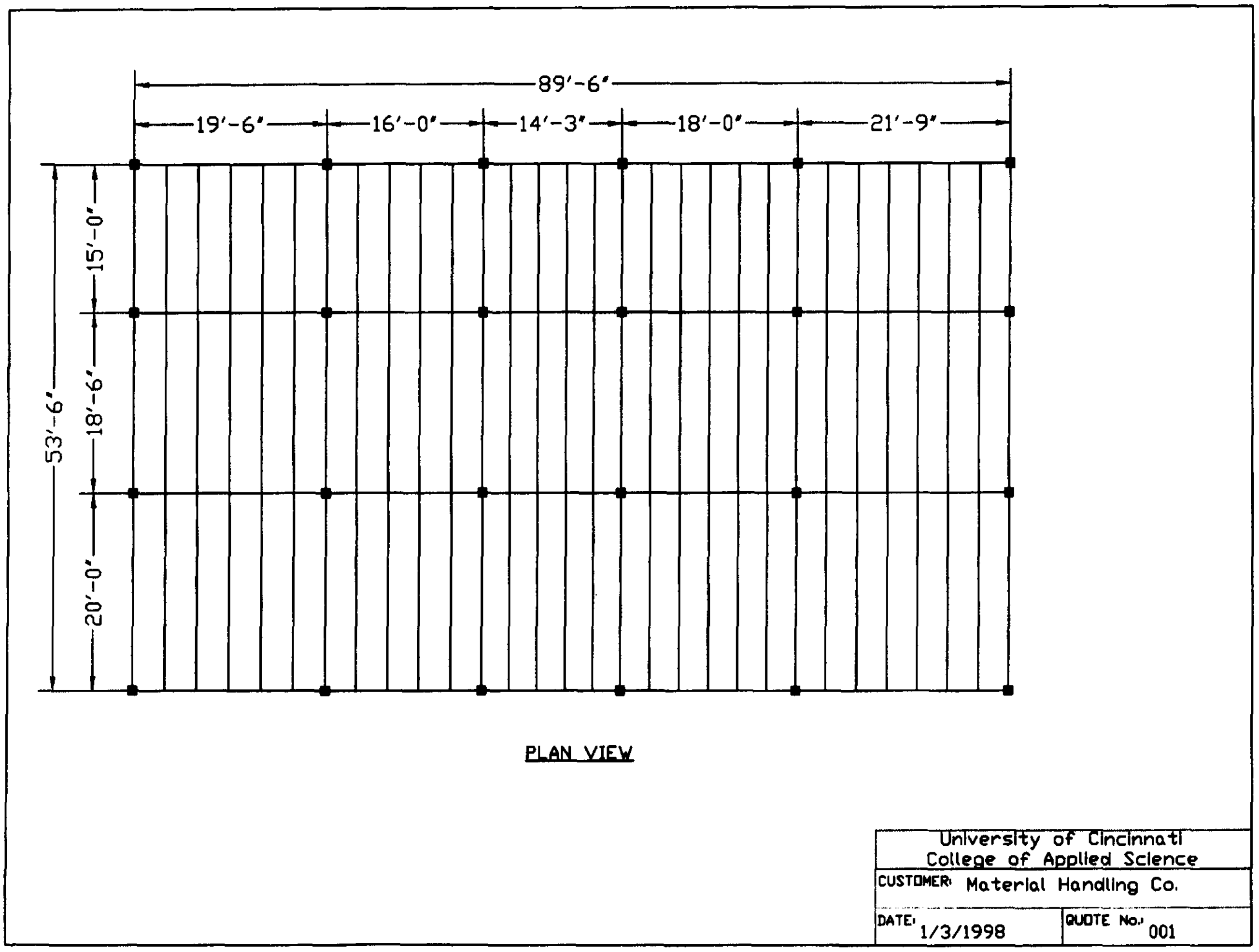

FIG. 4. PAM-Generated Layout Drawing

for assessing the applicability of the project. Access of clients to drawings, in this stage, solves many potential problems of interferences because it provides a visual image of what the structure will look like.

VE

The integration of the knowledge base and CAD tremendously expedites and improves the quality of the design process thereby permitting the development of several design alternatives that can be compared to select the least expensive. The PAM enables the user to produce quickly various design configurations and compare their costs. For example, a user can quickly evaluate the effect of increasing the beam span on cost and on the column loads transferred to the ground. Automating the design does not only result in cost savings but also makes it possible to account for other criteria such as eliminating interference problems and ensuring that column loads are transferred safely to existing slabs.

Expert Knowledge Not Available to Sales Personnel

Sales personnel are not always fully familiar with the design process and may as a result fail to make reliable quotes to potential customers in a timely manner. The implementation of PAM allows for the distribution of expert design knowledge to sales personnel, thereby improving overall design performance and reducing the design time. This is especially true in the case of mezzanine industry where product design requires highly skilled specialists with specific know-how and where the design has to meet tight manufacturing tolerances to allow fitting and assembling of prefabricated elements and to prevent interferences with existing facilities.

Reduction of Product Lead Time

The automatic generation of design allows the mezzanine manufacturer to respond quickly to the client's need for accurate price quotations. Reducing product lead times has become a significant competitive advantage in the construction industry. The automatic generation of design also increases engineering productivity, frees engineers from the tedious design details, and gives them more time to deal with the significant issues of engineering and design.

System Expandability and Modifiability

One of the important benefits of using production rules in knowledge representation is that it can be expanded and modified easily. It is easy to add more rules to handle situations not originally contemplated and to modify the knowledge to account for changes in code requirements (Elzarka and Bell 1995). This evolutionary improvement is characteristic of KBSs. If many domain experts contribute their knowledge to the system, the knowledge base over time may become more knowledgeable and capable of problem solving than any one of the experts who contributed to its development.

PAM IMPLEMENTATION

In its present form, PAM is implemented fully in a North American mezzanine manufacturing company. The PAM is the only tool that the sales personnel of the company are utilizing

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for preparing their daily quotations. Before the implementation of the program the quotation process was manual. The client would send a fax or call for a quotation. The sales person would acquire design information related to square footage, number of spans, length and width of structure, column spacing, expected loading, local codes, language of report, type of deck, and accessories like stairs, handrails, ladders, and gates. The design information was summarized on a standard questionnaire form. Sales personnel had two alternatives for preparing responsive quotations. The first and easier alternative was to use square footage costing where a unit square foot cost was multiplied by the area of the mezzanine. Markup for overhead and profit was then added. This procedure ignored the important effects of structure height, beam span, loading, and code requirements on the final cost. When the client accepted the quotation, the design information was submitted to the engineering department to design the mezzanine and estimate the required material. It was only after the completion of the preliminary design that an accurate engineering cost estimate could be developed. Very often the engineering price varied as much as 25% from the original quoted price. A low original quotation naturally led to a loss and a high quotation most often resulted in loosing potential customers.

The second alternative available to sales personnel for preparing quotations was to utilize load tables prepared by the engineering department to approximate the design of the deck, joists, beams, columns, and base plates. Although this procedure produced more accurate quotations, it was time consuming. Because the tables did not contain all the possible dimensions of the structural elements, interpolation and extrapolation took time and often resulted in errors. More over it was not always easy for sales personnel to use this method because it needed some engineering skills when determining the tributary areas required for calculating loads on structural elements. As a result sales personnel had to seek constantly engineering help to figure out appropriate member sizes. A detailed quotation for a mezzanine similar to the one illustrated in Fig. 3 required between 1.5 and 2.0 h.

Another problem with the manual quotation process was the inability to generate layout drawings. Clients usually require a layout drawing with the quotation to verify that the mezzanine actually will fit in the designated space. Clearance is another important factor that can be determined only after the exact size of the beams is calculated. Manual sketches that were prepared previously by sales personnel were not to scale and therefore could not help the client unless he had access to an engineer to verify the sketch. In many cases, clients approved manual sketches and later encountered interference problems at the time of installation when the mezzanine was already manufactured and shipped. Such interference problems created a hostile atmosphere and resulted in large cost increases.

One alternative for improving the quality of quotations was to add full-time engineers to the sales department; another alternative was to automate the quotation process. The automation effort required 4 man-months and a cost that is roughly equivalent to a 6-month salary of an intermediate structural engineer. The PAM implementation has reduced the time needed for preparing quotations from 2 h using the manual process to less than 10 min. Sales persons have not reported any difficulties using the system. The system leads the salesperson step by step, asking him/her for required information. The system is user friendly to a degree that salespersons without any computer literacy were trained in a 1-h session on how to use the system.

FUTURE ADDITIONS

Because of the modifiability and expandability of the system, it can be updated easily to include materials management capabilities. As the design is being completed by the knowledge base, the material requirements are collected in the database at the element level. The material can be summarized into material summary reports that display the total material requirements of the design. The material requirement data can be grouped into requisitions in the database and checked against the current inventory. A list of the members that are not found in the current inventory can be passed to the workshop to effect the manufacturing of the material. The materials management system also can contain the work-order number so that all work orders and promised manufacturing dates are incorporated into the database.

Scheduling capabilities also can be added. Quantities of bolts in the connections can be computed readily by the knowledge base. These quantities can be multiplied by the labor installation rates to determine the total craft labor-hours required to complete construction. The estimated duration is precise because it is based on actual design quantities.

CONCLUSIONS

The ability to integrate KBSs and CAD has streamlined the preconstruction analysis of mezzanine structures by accelerating the design process and improving the accuracy of the cost estimate. The CAD software available today, with its ability to link to external programs and to produce drawings automatically has made such integration possible. This integration also enhances the ability to provide insightful VE during design and permits the development of several design alternatives that can be compared against one another to select the least expensive. Streamlining preconstruction activities will become more and more important as the popularity of the design/build project delivery system continues to increase. The design/build approach requires that a project price and scope of work be guaranteed to the client prior to the final drawings and engineering design work.

An automated preconstruction analysis of mezzanine system was developed and described in the paper. The PAM capabilities include distribution of design expertise to a wide range of people in the organization, improved accuracy of cost estimates, improved speed of design, reduced product lead time, and automatic generation of drawings. The system supports different local codes of practices and can handle various loading requirements. The PAM development process has illustrated that CAD technology is advanced sufficiently to be integrated with external KBSs. Several other areas within the construction industry would likely benefit from such integration.

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