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Constructability in the Bridge Design Process

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TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

In the United States many Bridge structures have been designed without consideration for their unique construction problems. Many problems could have been avoided if construction knowledge and experience was utilized in the design process. A systematic process is needed to create and capture construction knowledge for use in the design process. This study was conducted to develop a system to capture construction considerations from field people and incorporate it into a knowledge-base for use by the bridge designers.

This report presents the results of this study. As a part of this study a micro computer based constructability system has been developed. The system is a user-friendly micro-computer database which codifies construction knowledge, provides easy access to specifications, and provides simple design computation checks for the designer. A structure for the final database was developed and used in the prototype system. A process for collecting, developing and maintaining the database is presented and explained. The study involved a constructability survey, interviews with designers and constructors, and visits to construction sites to collect constructability concepts. The report describes the development of the constructability system and addresses the future needs for the Iowa Department of Transportation to make the system operational. A user's manual for the system is included along with the report.

CHAPTER ONE

INTRODUCTION

Bridge structures are normally designed to high quality and safety standards but sometimes with not enough attention to construction methods and details. Construction problems encountered in the field can be costly. Many construction problems can be avoided with attention and consideration of the construction process during the design phase. Change orders, budget overruns, scope growth, and even litigation, in some instances, can be avoided by incorporating construction knowledge in the design process. This concept has been termed constructability.

Constructability has been defined as " the optimum use of construction knowledge and experience in the planning, design, procurement, and field operations to achieve overall project objectives(O'Connor, 1987)." Constructability requires a systematic process to create construction-oriented designs meeting the owner's project objectives in the areas of safety, cost, schedule, and maintainability.

The goal of constructability is <u>not</u> to cheapen the design, change the project objectives, or improve upon or take over the designer's responsibilities. The goal of constructability is to obtain broader knowledge earlier into the decision processes used in design.

This Iowa Department of Transportation study was sponsored to examine the ways that constructability concepts can be incorporated to collect, process, store, and retrieve construction knowledge. This system creates a means to capture past experience and knowledge for future use. The system uses the current state-of-the-art software technology to store and retrieve knowledge from past bridge projects in Iowa. The long term goal of the constructability process is to synthesize the experience and knowledge possessed collectively by individuals in bridge design and construction into a structured, user-friendly knowledge-based system.

The system as developed also provides a user-friendly environment for development of an overall design guide or manual for bridges. The system is capable of handling a wide variety of information needed during the design process, performing several design check functions and providing a structured storage and retrieval system for the database of design knowledge.

BACKGROUND

The term and concept of constructability has it's origin with a series of studies conducted by the Construction Industry Institute(CII) in Austin, Texas. These studies examined numerous projects around the country and found that the design decision process lacked the necessary construction knowledge and experience to realize the full potential of constructability benefits without sacrificing the integrity of other design considerations.

With the retirements of significant numbers of bridge designers from state transportation agencies throughout the United States, it is likely that much of the accumulated construction knowledge is, or soon will be, lost and the future quality and economical efficiency of designs might suffer. With design and construction as distinct processes, there is little opportunity for communication and cross-training. There is no mechanism currently to capture experience and share it from project to project or across the institution's organizational boundaries. There appears to be no systematic process for returning feedback from the field to the design departments for incorporation in future designs. Development of an approach for constructability input can address several of these problems and expedite a program of continuous improvement.

The CII studies showed that if constructability is implemented correctly, an owner can realize potentially large savings due to the designs being more construction-oriented. The Construction Industry Institute has developed a set of constructability concepts(CII,1987) from these studies, which can be applied to various types of projects, more specific concepts for the type of project and at the appropriate phase of construction can be developed. Each of the constructability concepts are listed and described briefly below:

<u>Constructability programs are made an integral part of project execution plans.</u>

For constructability to achieve its maximum impact it is important that it is addressed early in a project. The owner should address constructability in developing the execution plan for the project. Constructability needs to be addressed just like the other normal functional areas of contracting and procurement to achieve its full benefit. It should not be addressed as a special effort or done as an after-the-fact function in the design process. Including constructability in the execution plan creates the proper environment for thinking of the effect that all project decisions have on the construction process.

<u>Project planning actively involves construction knowledge and experience.</u>

Formal and informal planning efforts need to include people or sources of knowledge and experience in construction. The areas of knowledge which can be beneficial in the planning process include the following:

Availability and cost of materials

Availability and cost of skilled labor

Constraints and costs of transportation

Understanding of various construction methods

<u>Early construction involvement is considered in development of contracting strategy.</u>

Owners have various contracting philosophies concerning the division and assignment of responsibilities and the basis of payment provisions for design and construction services. The choice of approach will have an effect on the responsibility for collecting and coordinating constructability efforts. Where responsibility for design and construction is combined and contracted out, the owner has little responsibility for constructability. If the traditional design-bid-build approach is used, then the owner must coordinate or provide the constructability effort.

Overall project schedules are construction sensitive.

The planning process often addresses scheduling by setting the end date,performing the planning and design, and then requiring construction to be completed in the time remaining. While this approach may optimize the design and planning efforts, it creates inefficiencies in the construction phase. It is desirable to optimize the overall schedule. Compromises in all phases will be necessary.

Basic design approaches consider major methods.

The methods of construction have a major impact on the cost of a project. The methods are often dictated by the conceptual design and planning. By linking the design alternative being considered with the corresponding construction methods in the conceptual phase, the opportunity for significant savings can be realized. As design progresses, it is important to consider the potential linked changes in construction which would be required and the adjustment in cost that would be required.

Designs are configured to enable efficient construction.

The concept for a project is developed to conform to the criteria of the client. There may be several approaches which meet the usual criteria of safety, aesthetics, operability, and maintainability. Constructability should also receive the appropriate consideration. The following factors should be a part of the thinking that goes into a constructability evaluation of design:

Simplicity

Flexibility

Sequencing

Substitutions

Labor skill/availability

<u>Design elements are standardized.</u>

The appropriate use of standardization can have several benefits. These include increased productivity/quality from the realization of repetitive field operations,reduction in design time, savings from volume discounts in purchasing, and simplified materials management. Some caution should be taken to insure that creativity is not stifled and that the long term effect is not one of stagnation and outdated design elements for the sake of standardization.

<u>Construction efficiency is considered in specification development.</u>

A major factor affecting the cost of a project is the quality of the specifications. Just as with designs, constructability should be considered when standard specifications are being developed and applied. The same factors that apply constructability evaluation of design also apply to specifications.

Designs promote construction accessibility of personnel, material, and equipment.

Access during construction of personnel, materials, and equipment should be considered during the design process. The impacts on safety, productivity and schedule are acute and have a significant multiplier effect on the cost for construction. On large-scale labor intensive or material intensive projects a careful review of accessibility should accompany the design.

For constructability to be successful, all members of the administrative, contracting,design and construction organization must practice this philosophy. From the Construction Industry Institute studies, it was found that the most successful constructability programs have the following(Construction Industry Institute, 1987,p.1-2):

"1. Clear communication of senior management's commitment and support of constructability.

2. Single point executive sponsorship of the program.

3. A permanent corporate program and a tailored implementing program within each project.

4. "User friendly" procedures and methodologies.

5. A corporate "lessons learned" database.

6. Training where necessary.

7. Easy appraisal and feedback."

As can be seen, the previous work of others has documented the general principles to be followed for having a successful approach to constructability improvements. These principles appear sound and serve as the foundation for development of the concepts for the Iowa Department of Transportation Office of Bridge Design.

Other more specific recommendations for specific types of structures have been reported(Rowings and Kaspar,1991;Kaspar and Rowings,1991) but these were both related to cable-stayed structures and are of limited value for the more routine design challenges faced by the Bridge Office.

RESEARCH METHODOLOGY

The investigation of the opportunities for constructability for bridge projects and the development of an initial knowledge-base consisted of four major steps:

1. A literature review to collect information regarding constructability.
2. A survey of designers and bridge contractors to collect preliminary information on bridge constructability concepts.
3. Development of constructability concepts for consideration from contractors through personal visits to project sites.
4. Development of a structured, user-friendly microcomputer database system for use by bridge designers.

It became apparent during the field interview process that a system for continued collection of constructability concepts would be needed to keep the knowledge-base up to date. A procedure for ongoing use of the system and for continued collection of concepts was developed.

Each of the above tasks are described in greater detail below:
Task 1 - A literature review was performed to identify general constructability concepts which might be applicable to the bridge design process. The purpose of identifying the general principles was to guide the more specific search and provide a structure to develop field input. Once the general concepts were identified, literature containing detailed constructability concepts was also sought. Little information of a detailed nature exists in the published literature relative to bridges. Literature pertaining to specific types of bridges, such as cable-stayed and segmental, was examined for ideas that might have merit across a wider range of bridge types.

Typical standard bridge plans, details, specifications, and manufacturer information were collected to determine the types of information that is used by the bridge designer and to develop a format for the constructability knowledge-base. These plans were reviewed for areas where it might be possible to apply several of the general constructability concepts. As the project progressed the researchers also gathered and reviewed other design aids such as design department memos and a dated design manual from California. Several constructability considerations were developed from the literature for review in the prototyping phase of the constructability concept review system.

Task 2 - Upon completion of the literature review a constructability survey was developed (see Appendix 1). The survey was mailed to 36 contractors and designers to collect preliminary information on constructability considerations for Iowa bridge design projects. The general areas of inquiry included the following:

A. How should designs be configured to enable efficient construction?

B. How can construction productivity be enhanced through standardized design elements?

C. What can be done with specifications to promote construction efficiency?

D. When can the use of module/preassembly concepts facilitate fabrication, transportation, and installation of components during construction?

E. How can access be improved for construction efficiency?

F. Which types of design details require more time and human resources?

G. Which design details cause more temporary construction activity?

Task 3 - Once the survey results were reviewed appointments were made and interviews were conducted with several bridge contractors, county engineers, and personnel in the Iowa Department of Transportation Construction Department. These interviews were used to develop more specific recommendations for constructability concepts for bridges. These interviews focused on getting specific ideas in the following areas:

A. Design details

B. Access to construction

C. Prefabrication issues

D. Design simplicity and flexibility

E. Forming details

F. Staging details

G. Temporary structures during construction

Several field trips to active bridge construction projects representing the range of bridge types were made. Through these visits and interviews with the field construction supervisors, several initial constructability considerations were developed for testing in the concept review system.

Task 4 - The previous tasks were in support of the major goal of this project which was the development of a structured, user-friendly microcomputer database system for codifying construction knowledge for bridge designers. The development of the system began with the development of the forms and procedures for collecting and evaluating constructability concepts from the field personnel familiar with construction. This development followed the general principles suggested by previous CII studies for a workable process. The organizational structure of the Department of Transportation was reviewed to insure that the responsible parties would have the opportunity to review suggestions and that the process would be efficient and coordinated.

The type of information that could likely be supplied by someone in the field was determined from field visits to construction sites. Actual constructability concepts were collected from Iowa bridge projects during the summer of 1990.

Visits were made to various bridge types all across the state and the researchers met with Iowa Department of Transportation personnel and contractor representatives on the projects.

The constructability knowledge-base system requires a logical and easily understandable classification structure to be useful. A classification scheme was developed which would allow cataloging and retrieval of constructability concepts. The classification system was developed based on initial discussions with personnel in Bridge Design. The initial classification scheme generally follows the breakdown of a bridge into its physical components(i.e.piling ,pile cap, etc.). Near the end of the research, an expanded system was proposed by the individual assigned to implement the system in Bridge Design. This alternative structure appears to represent a considerable enhancement of the constructability system to other areas of design and other functional areas of the Iowa Department of Transportation. This approach is consistent with the principles of constructability developed by CII and is currently being evaluated for its feasibility for development at this time by the Iowa Department of Transportation.

Several software systems and microcomputer platforms were evaluated for the type information which would be contained in the knowledge-base. Also, the ability to access and cross-reference was a key factor in the evaluation of an appropriate system. The features of the system are described in Chapter 3. The system was developed using *Knowledgepro* software which works in a *Windows* environment. The system deploys a series of screens for displaying information and uses the concept of hypertext for activating the cross-referencing capability of the system.

Various types of data were input into the system to be able to demonstrate the capability of the system as an aid to the designer. Several constructability considerations from the field were input into the system and the appropriate cross-references were developed. The system was tested and further features were added. These include the capability to scan in documents such as the standard specifications and the ability to develop calculation routines for checking dimensional tolerances. Each serve to further the usefulness, efficiency, and user-friendliness of the system.

Several demonstrations of the system were performed for personnel from Bridge Design and their feedback and input was obtained. Further minor modifications were made to enhance the friendliness of the overall system.

It was determined that further groups would likely need to become involved in the review process for constructability concepts since many of the ideas require evaluation by more than one discipline or functional group within the Department of Transportation. It was suggested by representatives from Bridge Design that the coordinating department should be the Office of Construction since they would have the vision across various functional offices (e.g. Road Design, Maintenance, Etc.). Therefore, the concepts in the demonstration system are for illustration purposes only at this time. Application and development of a complete constructability knowledge-base with complete data was not called for in this project but may be accomplished in a future phase.

CHAPTER TWO

CONSTRUCTABILITY SURVEY

A survey(see Appendix 1) to collect specific ideas for constructability was sent to 36 contractors, designers, Iowa DOT construction resident engineers, and county engineers. The survey was conducted during December of 1989 and January of 1990. Thirteen useable responses were received representing a return rate of about 36 percent. The organizations participating in this survey included the following:

A.M. Cohron & Son, Inc.

Brennen Construction

Christensen Bros., Inc.

Prestressed Concrete

Merryman Bridge Const. Co.

Cramer Bros.

Cunningham-Reis Company

Taylor Const. Inc.

Elkhorn Const, Co.

Jefferson Construction Residency

Kossuth County Engineer's Office

The responses for each question were reviewed carefully and the input received was used to create constructability proposals for trial use in the review system developed for evaluation and inclusion in the knowledge-base. These responses also provided guidance for issues to raise during the in-depth interviews with contractors and county engineers. The responses to the questionnaires varied substantially with each having one or more unique problem with some design detail that was encountered during the last construction season. From the length and completeness of the responses it appeared that contractors are not prone to responding to the types of questions asked with the necessary graphical and written responses requested. The researchers felt that the questionnaire was too far removed from the construction process to get the maximum benefit from the constructor's knowledge. While several very detailed responses were received, it was felt that a better approach to collect concepts would be to visit construction projects during the process.

INTERVIEW RESULTS

Following the surveys, interviews were conducted with five bridge contractors,two county engineers, and two individuals in the Office of Construction of the Iowa Department of Transportation during the next month. The interviews were scheduled with individuals who were recommended by the Iowa Department of Transportation and who had not participated in the previous written survey.

The interviews yielded many concepts which fit within the framework of constructability principles. These ideas built upon the information received from the written survey. It appeared again that the memory of the individual was taxed hard to come up with specific areas for improved design for construction efficiency when a project was not currently being worked on by the constructor.

An additional approach of site visits during construction was also employed. Eight different bridge projects were visited during the summer of 1990 around the state of Iowa. These included a variety of structures in various phases of construction. At each site the contractor's supervisor was interviewed. At most sites the individual responsible for construction from the Iowa Department of Transportation was also interviewed. The purpose of these interviews was to collect constructability concepts for inclusion in the knowledge-base. This method prove to deliver the most detailed and broad set of constructability considerations of the three methods of data collection.

CHAPTER THREE

The study examined the way that information and knowledge could be collected, evaluated, stored, and retrieved for use in the design of bridges. The research resulted in the development of two distinct systems; the Constructability Issue Review Process, and the Bridge Design Constructability Knowledgebase. The constructability issue review process was developed as a means to formalize the process of collecting constructability issues from the field, evaluating the ideas for merit, and determining if the issue warrants an addition to the current constructability knowledge. Constructability issues that have been approved for addition to the accumulated knowledge are then added to the Bridge Design Constructability Knowledgebase.

CONSTRUCTABILITY ISSUES REVIEW PROCESS

The constructability issue review process is initiated by the submission of a Constructability Review Form (CRF). The first part of the CRF is the proposal as shown in Figure 1. This form collects information about the individual submitting the form, a description of the problem, suggestions for improvements, and potential benefits or drawbacks of the improvement suggestions.

In Figure 2 the area labeled "1.0 Proposal Initiation" indicates that the CRF can be initiated from several sources. Obviously, constructability issues can come from construction and inspection personnel, but they can also come from fabricators, shop

Constructability Review Form
Step A: Proposal

Name: (individual submitting this proposal)				Date:
Title:	Telephone:			Address:
Project Description:			County:	
			Project No:	
			Design No:	

Problem Description: (make reference to appropriate details, drawings, specifications, etc.)

Suggested Improvement: (Include sketches, details, examples to clarify the suggestion)

Benefits / Drawbacks: (describe anticipated advantages of the improvement suggested and probable drawbacks, if any)

Other Comments:	Mail completed form to: Construction Department Iowa Dept. of Transportation 800 Lincoln Way Ames, IA 50010

Figure 1 - Constructability Proposal Form

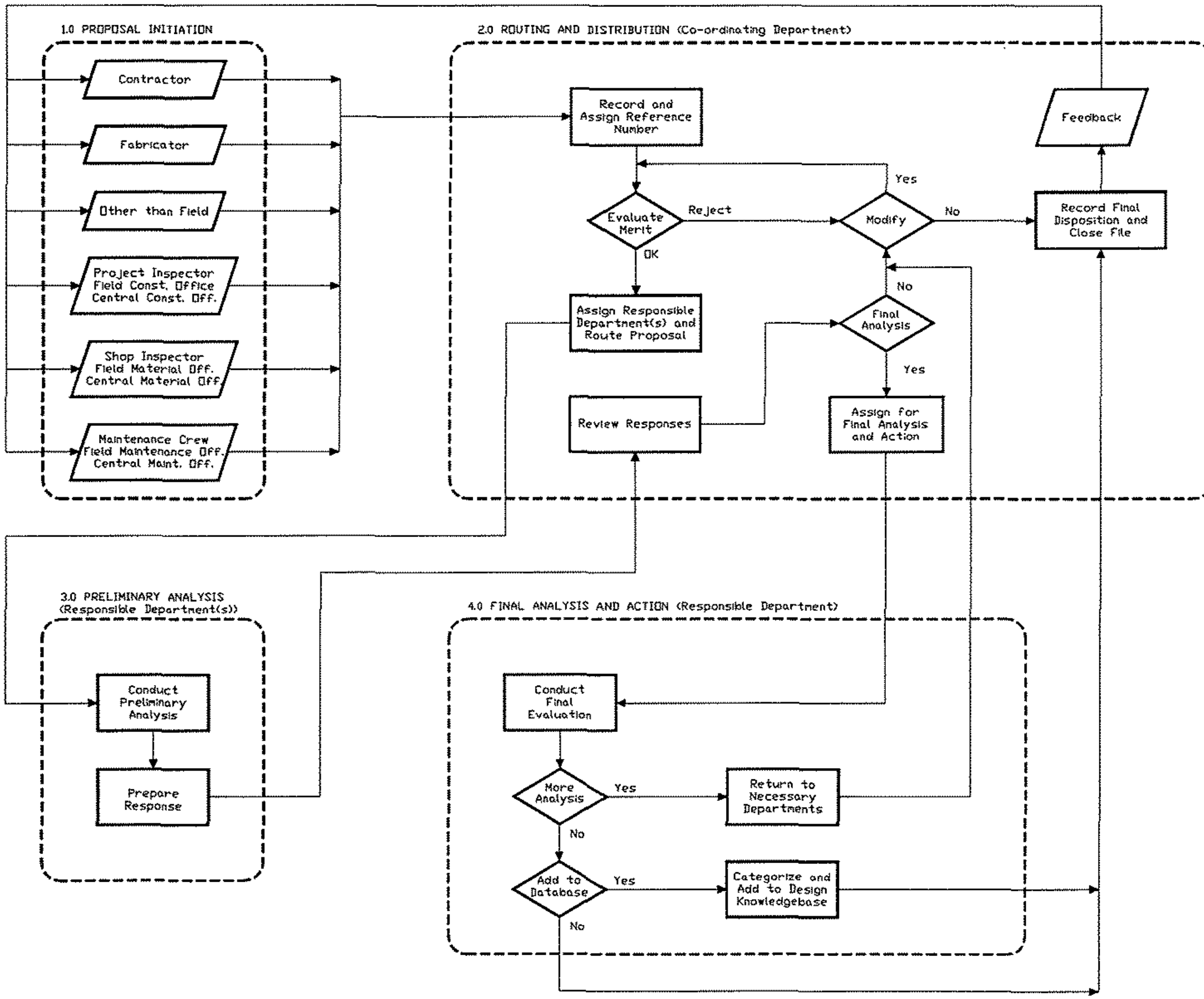

Figure 2 - Constructability Review Process

inspectors, materials offices, and from maintenance personnel. It is also possible that proposals could be initiated in areas that are not identified in this figure.

Once a proposal is completed it is returned to the coordinating department as shown in Figure 1. Considering the range of potential responses, it has been suggested that the coordinating department should probably be the Office of Construction since most of the proposals submitted would be generated through construction activities and would cover a broader group of disciplines than bridge design. A similar system could be developed in other areas of the DOT such as road design.

The first function of the coordinating department, once a proposal has been received, is to record the submission and assign a reference number. Also, at this point, the proposal is reviewed to determine if it has potential merit and should advance to preliminary analysis. If it is determined that the proposal has no merit, but that with some modification it actually presents a valid issue it could still continue to preliminary analysis with the modifications noted. For a proposal that has no merit and to which there are no apparent modifications that could salvage it, the issue is closed. Note in Figure 2 that a proposal of this type enters a feedback function. At this point a response is returned to the individual that made the submission explaining why no action was taken regarding the submitted proposal. Pursuant to the research function of collecting constructability issues from field personnel it was apparent that an incentive for encouraging ideas from the field was some feedback indicating the disposition of the submissions. If the feedback is not delivered, further submissions are less likely since the submitters do not believe their suggestions are given a sincere evaluation.

For proposals that warrant further analysis, the coordinating office then determines which offices should perform the preliminary analysis and routes a copy of the proposal along with the proper attachments to these disiplines. Figure 3 shows an example of a routing sheet. The routing sheet is used to record when a proposal was sent to a department for preliminary analysis, when it is expected to be returned, and the date that it was actually returned. This form stays with the coordinating department and is used to determine the progress of the proposal throughout the evaluation process. Figure 4 shows an example of the response form to be attached to the proposal and any modifications. An individual will be identified in the office doing the preliminary analysis to be responsible for completing the form and returning it to the coordinating office by the return date indicated on the form. Names of individuals consulted in preparing the response should also be noted on the form in the event further clarification is required. As Figure 2 indicates, the responses generated by the preliminary analysis process will be returned to the coordinating office for evaluation and assignment for final evaluation.

The coordinating office, after collecting all of the responses from the preliminary analysis departments, makes a determination as to whether or not the proposal should be submitted for final

Constructability Review Form

Routing Sheet

	Proposal No:
Co-ordinating Department:	Date Received:
Coordinator's name:	Phone:

Preliminary Analysis

	Department	Date Sent	Date Expected	Date Received
1				
2				
3				
4				
5				
6				
7				

	Department	Name	Phone
1			
2			
3			
4			
5			
6			
7			

Final Analysis

Department	Date Sent	Date Expected	Date Received

Department	Name	Phone

Person providing feedback:	Date:

Comments:

Figure 3 - Constructability Routing Form

Constructability Review Form

Step B: Preliminary Analysis

		Proposal No:
Department:		Date forwarded:
Name: (individual responding to proposal)		**Please reply by:**
Title:	Office:	Phone:

Response to the Proposal: (describe reasons for agreeing or diasgreeing with the proposal)

Suggested changes: (make recommendations that may improve value of proposal)

Individuals consulted in preparing the response

Name	Title	Department	Date

Figure 4 - Constructability Analysis Form

analysis. An alternative to this step would mandate that a proposal that has been submitted for preliminary analysis be submitted for final analysis and action. Consider, however, the case where the initial proposal's merit was marginal and that after reviewing the responses from the preliminary analyses it was obvious that the proposal did not warrant further evaluation. Departmental resources could be conserved by closing the proposal at this point. A possibility also exists that the preliminary analysis presents information that suggests modifications to the original proposal that would then warrant a new evaluation. A proposal not warranting final analysis could then be modified and re-enter the preliminary phase or it would be closed and the feedback function would be initiated.

A proposal that merits final analysis would then, along with all information collected to this point, be given to the department upon which the proposal had a direct impact. The form shown in Figure 5 is attached to the proposal to record the outcome of the final analysis. For the purpose of this research, the department doing the final analysis would be the Office of Bridge design. This department would then consider all of the analyses to date along with its own, and make a decision as to whether this proposal would become part of the current constructability knowledge. If the proposal was rejected it would be returned to the coordinating department for disposition. A proposal that was accepted would then be added to the Bridge Design Constructability Knowledgebase. Note that a positive response is also returned to the coordinating

Constructability Review Form

Step C: Final Analysis

Proposal No:		
Department:		Date forwarded:
Name: (individual responding to proposal)		Please reply by:
Title:	Office:	Phone:

Final Action Taken: (check one)

☐ Accepted ☐ Declined ☐ Further Study

If Accepted, describe how proposal will be incorporated into current constructability knowledgebase.
If Declined, explain the reason for declining the proposal.
If Further study recommended, indicate what should be reviewed and by whom.

Date entered into permenant records.

Figure 5 - Constructability Final Analysis

department so that the file can be closed and a response can be given to the individual submitting the proposal.

BRIDGE DESIGN CONSTRUCTABILITY KNOWLEDGEBASE

Knowledge-base Objectives

Many of the system's objectives were determined by the existing computer capabilities in the bridge design department. Exposure to PC's is minimal. It was obvious that the knowledge-base would need to be very user-friendly and need to present information in a format that was easily understood. Since this system is intended to be very dynamic in order to pace new construction techniques and technologies relevant to bridge design, the process of adding new constructability concepts had to be as uncomplicated as possible. A large part of the success of this system revolves around making it as practical and as easy to use as possible.

Software and Hardware Selection

After considerable research and discussion, a software package was selected for the development of the bridge design knowledge-base. The package chosen was *KnowledgePro for Windows* which is produced by Knowledge Garden, Inc. *KnowledgePro for Windows* is an application development tool for Microsoft Windows 3.0. *KnowledgePro for Windows* contains built-in expert systems technology and hypertext capabilities, important functions for this application. All of the information stored in the knowledge-base is contained in simple ASCII text files. *KnowledgePro for Window's* predecessor, KnowledgePro for DOS, is an expert system development tool, with an inference engine and full forward- and backward-chaining. *KnowledgePro for Windows* inherited some of these features--the use of a knowledge base and topics instead of source code files and functions. This allows the use of rule-based artificial intelligence in applications developed with *KnowledgePro for Windows*.

Other software used, besides the Windows 3.0 environment, included *ImageStar* for controlling the scanner, *Paintbrush* for graphic editing, *ReadRight* for optical character recognition (OCR), and *PCWrite* for ASCII text editing. With the exception of *PCWrite*, all of these applications are *Windows 3.0* based. *ReadRight* allows using the scanner to convert text documents into ASCII text files, eliminating much of the typing involved in entering large amounts of text into the knowledge base.

This group of software provides some very powerful tools for the development of this application. Likewise, it also requires a powerful computer in order to provide optimum functionality and useability. Minimum requirements for the hardware are as follows:

386DX based PC with 4MB of memory

386 co-processor

150MB hard drive

Color VGA monitor

mouse

B&W full page 300 dpi scanner

The Knowledge-Base

The easiest way to explain the function and feel of the knowledge-base is to present some representative screens and explain their operation. Figure 6 shows the initial screen presented to the user. This screen also becomes a sort of homescreen that the user can always return to access a different thread of knowledge. The title of this screen is INDEX and is displayed in the titlebar at the top of the screen. The title changes with each screen to provide a cue to the user as to the name of the current screen. Along the top of the screen just below the title bar is a row of nine buttons. These buttons all have functions related to their name and can be activated by clicking on them with the mouse. The button's functions are as follows:

Index - Returns the user to the INDEX or initial screen.

Back - Displays the previous screen viewed.

Where - Opens a window and displays a list of titles of screens viewed prior to and including the current window. The Back button will always display the window directly above the last title on the list.

Reset - Returns the user to the INDEX screen and clears the Where list. This is just like starting the program initially.

Info - When viewing a constructability topic pressing this button open a window that provides information on the person that submitted the issue including the person's name, company, position, project description, location, and number, date, and the date entered into the system.

Direct - This opens a small window which prompts the user for the name of the topic he/she wishes to view. This provides direct access to the constructability topics, bypassing the normal menu selection process.

Print - This button will print the contents of the current window including the graphics.

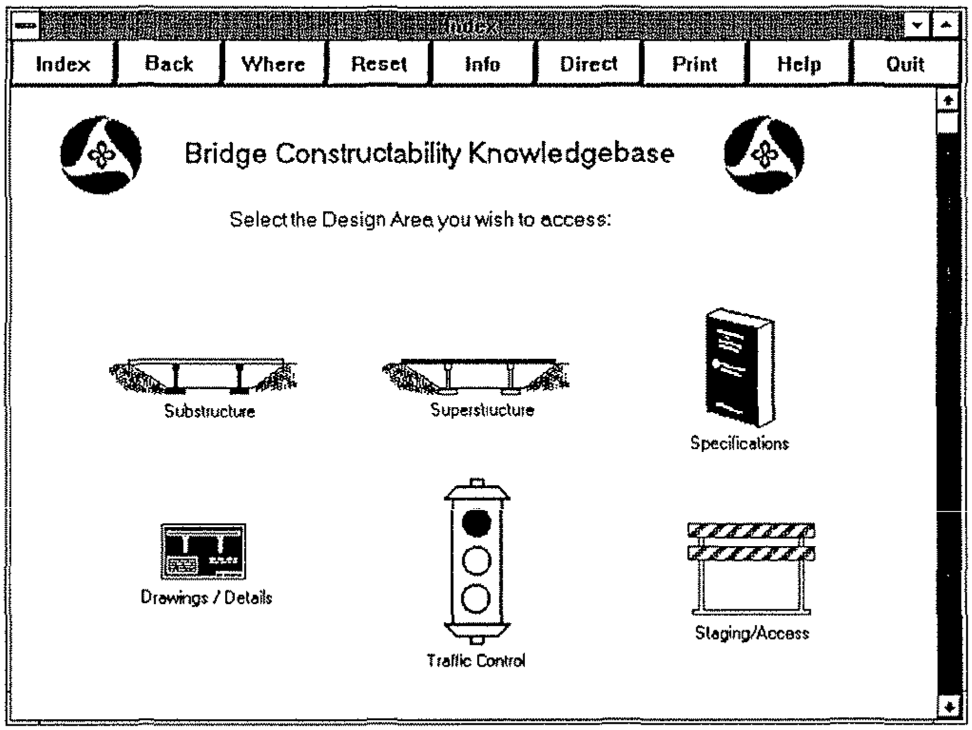

Figure 6 - Microcomputer Menu Screen

Help - This provides an on-line hypertext help application similar in structure to the windows help.

Quit - This button terminates the current session.

The window can be modified and the size can be changed. The buttons will remain the same size and wrap to the next line as necessary to accommodate a width less than the full screen. A scroll bar is provided along the right side to view topics that are longer in length than one screen. All of the functions mentioned so far are consistent to every screen in the knowledge-base. This helps build a consistent look and feel to minimize confusion and increase productivity and ease of use.

Besides the title and the Iowa Department of Transportation logo there are six graphics displayed on the INDEX screen. These graphics represent the six design areas containing constructability issues in the knowledge-base. Each of these graphics is a hyper-region. As the cursor passes over these regions it changes from the familiar arrow into a hand with the index finger raised as if to point. This indicates to the user that this is a hyper-region and that clicking on this area will activate the associated function. For example clicking on the Substructure graphic will present a screen containing a subtopic relative to Substructure such as drilled shafts, piling, piers, etc. These items are presented in a list of hypertext segments. Clicking on any of the items in the list will then show another list of constructability concerns for that particular item. Choosing an item in the constructability concerns list will then present the constructability topic.

Figure 7 is an example of a constructability concern involving the lower reinforcement mat in pile caps. The graphic displayed on this screen was scanned from the original drawings using the previously mentioned scanner and ImageStar. It was then cleaned up and a red circle highlighting a point of interest was added using Paintbrush. Paintbrush was then used to save the graphic in the form of a bitmap for use in the knowledge-base. These graphics can be then displayed by KnowledgePro very easily in any screen desired. The bottom of the page indicates something called related topics. *These can be a legal topic in any of the files in the* system. Clicking on a related topic will then display the screen associated with that topic. By means of providing hyper-links such as these to other topics the user can begin to follow threads through the knowledge in any manner that he/she desires.

For example Figure 8 shows the screen that would be displayed if the related topic from the previous screen were to be chosen. This topic is part of the design area titled Specification of the INDEX screen. This area was developed by scanning in pages of the specifications and then converting them to ASCII text using the ReadRight optical character recognition software. The specifications are already numerically coded so this was exploited to provide topic titles. Whenever a reference to another specification appears in the text it is made hypertext providing instant access to any referenced specifications. These screens can also contain related topics in other design areas. The robustness of the system is directly proportional to the amount of hyperlinks

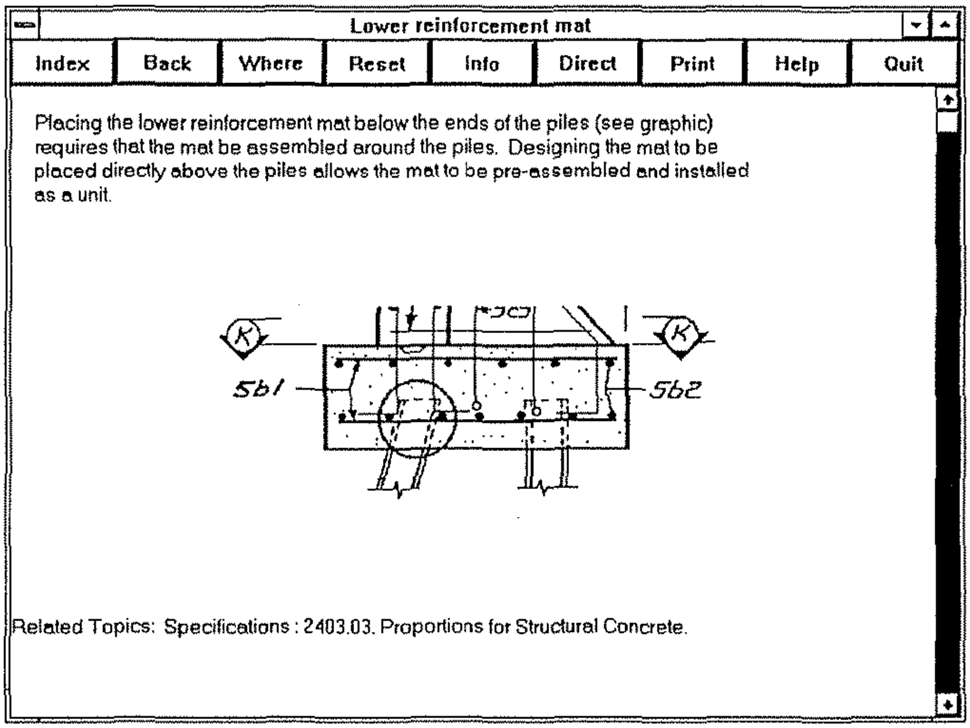

Figure 7 - Sample Graphic Data Screen

Index | Back | Where | Reset | Info | Direct | Print | Help | Quit

2403.03 PROPORTIONS FOR STRUCTURAL CONCRETE.

Materials for structural concrete may be mixed in proportions for any of the mixes allowed for the class of concrete specified in the contract documents, provided the gradation of each aggregate conforms to the gradation required for that proportion. The plans will indicate where each class is to be used and the approximate quantities of each class. At the Contractor's option, Class D proportions may be substituted for Class C proportions. With specific approval of the Engineer, proportions listed in 2301.04E or normal proportions using Type III cement may be used for Class C concrete.

A. Proportions for Separate Fine and Coarse Aggregate.

BASIC ABSOLUTE VOLUMES OF MATERIALS PER
UNIT VOLUME OF CONCRETE*

Class	Mix No.	Cement Minimum	Water	Entr. Air	Fine Agg.	Coarse Agg.
C	C2	.110202	.148144	.06	.272662	.408992
	C3	.114172	.153840	.06	.301895	.370093
	C4	.118330	.159808	.06	.330931	.330931
	C5	.122867	.166318	.06	.358448	.292367
	C6	.127782	.173371	.06	.384308	.254539
X	X2	.124379	.165318	.00	.284121	.426182
	X3	.129105	.171599	.00	.314683	.384613

Figure 8 - Sample Specification Screen

that are developed. This system attempts to establish these links where ever possible. Another very important feature of the system is the ability to make use of the expert system capabilities of KnowledgePro.

Figure 9 shows a simple example of that capability. This can be used to check the spacing between reinforcing bar in a circular pier. There are three possible answers given to the user based on the calculated spacing. If the spacing is too small a window indicating a warning is opened and the user is told to use a larger diameter reinforcing bar to reduce the number required, if the spacing is within a certain range a caution window is opened with suggestions for aggregate size and pouring methods, or if the spacing is adequate an OK window is displayed.

Adding to the Knowledge-base

As mentioned earlier a key to the success of the system lies in the ability to maintain the system and add new information easily. To make the addition of information as easy as possible all of the information displayed in the knowledge-base screens is stored in simple ASCII text files. An example of the text file that was used to create the screen in Figure 7 is listed here:

```
//lower reinforcement mat

     Placing the lower reinforcement mat below the ends of the
piles (see graphic) requires that the mat be assembled around
the piles. Designing the mat to be placed directly above the
piles allows the mat to be pre-assembled and installed as a
unit.

Related Topics:   Specifications : #m2403.03.#m Proportions
     for Structural Concrete.
#cgraphic    is    load_bitmap    ('ida.bmp').        bitmap
     (?graphic,20,10).
```

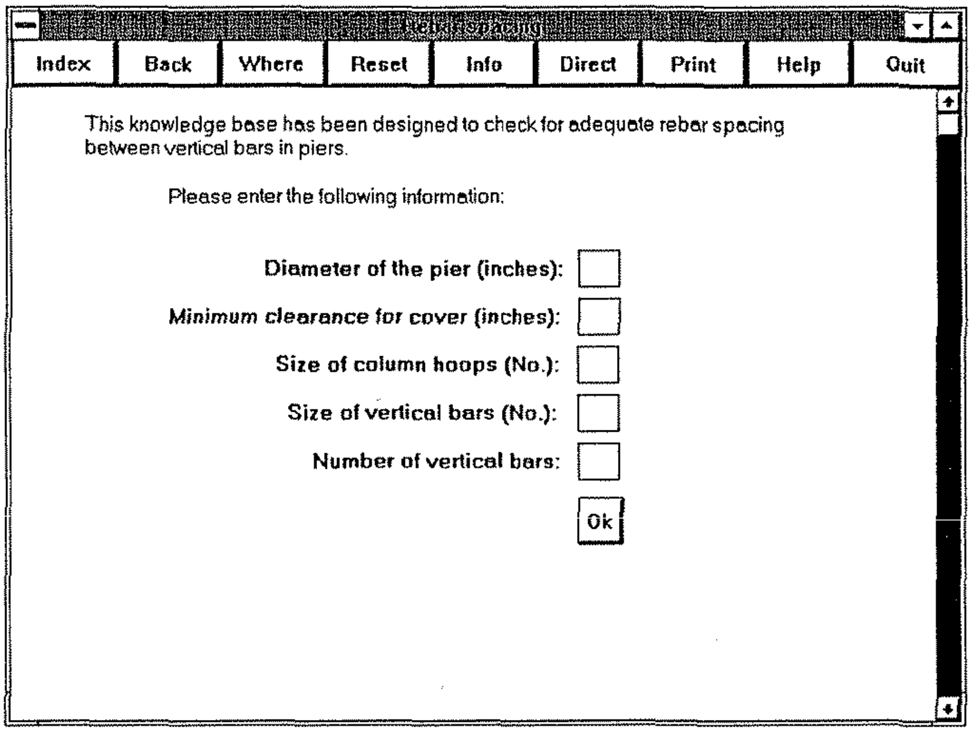

Figure 9 - Sample Calculation Screen

```
info    gets    ['John    Pouge','Guetzko    Construction','
IX-218-7(72)--3P-07    ','Ansborough
Avenue','Blackhawk','Waterloo','May    15,    1990','October
18, 1990','Substructure','PileCaps','Reinforcement','']. #c
#cwherei gets 'Lower Reinforcement Mat'. #c
#crelated_1 is ['spec.hyp','2403.03.'].#c
```

Any text is displayed in the window as presented. Text that is surrounded by #m's becomes hypertext and is displayed in the color green to indicate this. All of the information that is surrounded by the #c's are items that are compiled and executed by the program. These lines display the graphic, pass information to the info topic, pass the name of the topic to the where list, and tell the program where to find the related topics.

These are all of the items that need to be used for any topic and they are consistent across all of the items in the knowledge-base. This consistency make it quite easy to train personnel in how to add information to the knowledge-base. The only additional software the person needs is a word processor that can handle ASCII text.

Graphical information is collected by means of scanning drawing or sketches as necessary to clarify a particular issue. Any B&W scanner including a hand scanner would be suitable for the task.

Knowledge-base Structure

Figure 10 shows the originally proposed basic organizational structure of the knowledge-base. Obviously many of the subcategories are incomplete, but it does give an impression of the general structure. Other than the initial screen, any of the subcategories are also included in the text files of the knowledge-

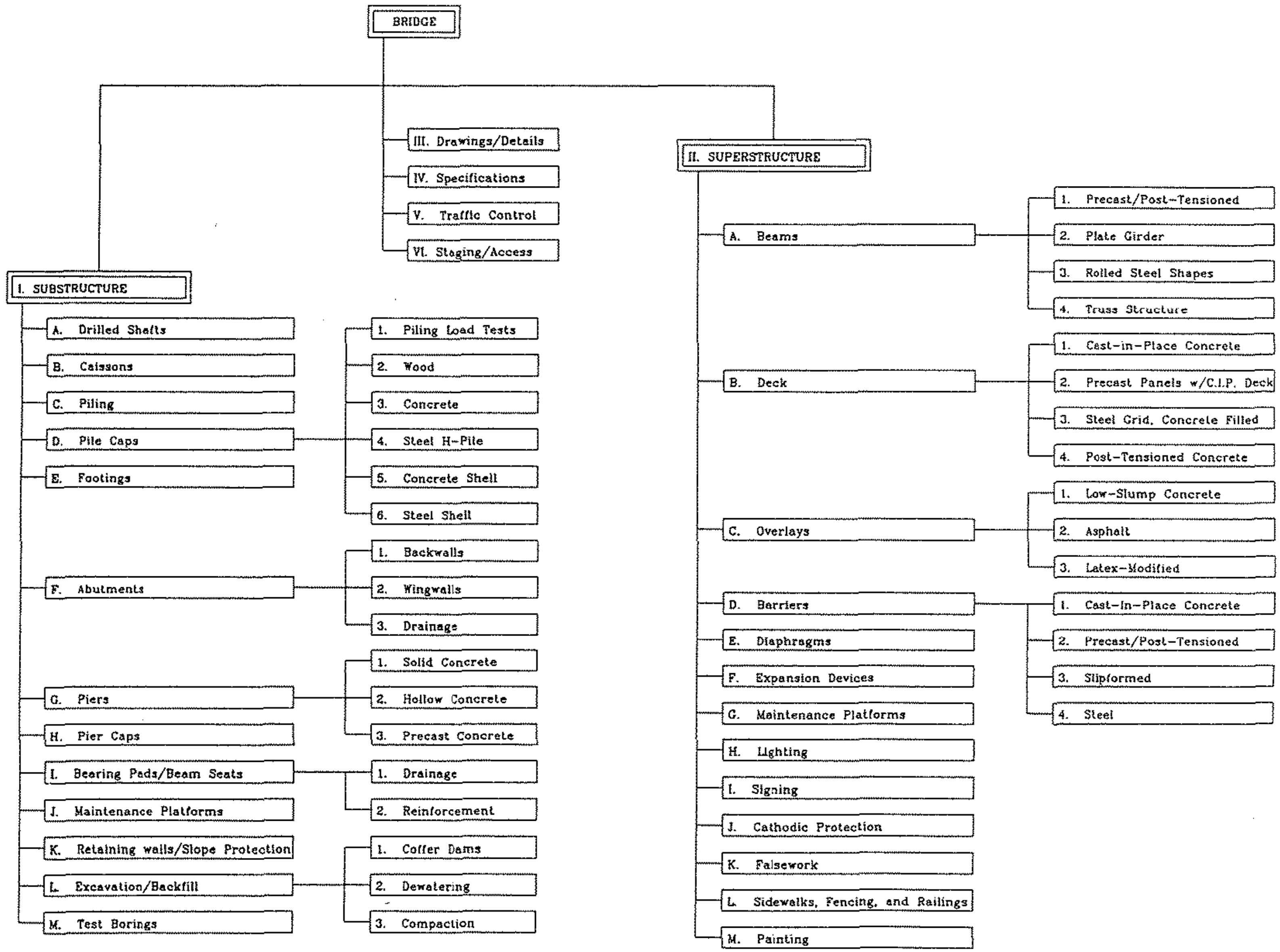

Figure 10 - Knowledge-Base Structure

base. The advantage of this is that the structure of the knowledge-base can be modified or expanded as easily as adding information to the knowledge-base itself. The structure is also very flexible, allowing references to any constructability issue to occur on virtually any screen other than the initial index screen.

Appendix 2 contains a user's manual and recommended configuration for the system to be used in the Office of Bridge Design. The Iowa Department of Transportation is pursuing purchase of the necessary hardware and software at this time.

CHAPTER FOUR

Summary

Constructability opportunities in bridge design exist. The development and application of constructability concepts has the potential for creating better designs. The research has led to the collection of several potential constructability concepts and to a system for collection and evaluation of improvements. Most of the specific constructability considerations developed from construction input deal with changes to standard details such as forming details, embedment placement, and reinforcing steel placement. The system for evaluation involves a review procedure by the Iowa Department of Transportation to consider opportunities for change in details and standards. The review process always ends with feedback to the originator to encourage additional future input.

The most effective approach to integrating construction knowledge into the design is through early proactive consideration of construction aspects of a project. This has been shown to be more cost effective than altering the design at a later stage to react to the construction input from a review. To achieve this it is necessary for the designer to possess or have access to the construction knowledge or experience during the design process. This construction knowledge will be changing as new methods and materials are developed. The knowledge and experience base of the designer needs to progress continuously also. It appears appropriate to maintain, in some form, the up-to-date construction knowledge in a form which is readily accessible by all bridge designers as they develop their designs.

The researchers developed a microcomputer knowledge-base for use by the Office of Bridge Design and others at the Iowa Department of Transportation. The constructability knowledge-base system was developed using *Knowledgepro for Windows*. The system has been developed using a simple to understand classification system for storing and retrieving concepts as the design progresses. The system has been designed to make it simple to access and easy to update and add information. The system as it currently exists presents several examples to illustrate the potential uses and capabilities of the knowledge-base for the Bridge Office.

Conclusions

There exists an opportunity to continually seek and make improvements in design by factoring in construction knowledge in the bridge design process. A survey of constructors, interviews with constructors and visits to construction sites yielded a few examples of constructability considerations that might have merit to improve future designs.

The knowledge-base that was developed for use in storing and retrieving constructability information has even greater potential to store and contain a broader set of knowledge needed by the designer including design standards, design checklists, computational models, design guidelines, vendor data and other pertinent design knowledge. The knowledge-base also has the potential for expansion into construction and design knowledge for other design areas such as roads.

Recommendations

The true value of the system which was developed can not be determined until the prototype system is utilized in Bridge Design. The system should be set up and it's use and effectiveness evaluated by both the Bridge Design Office and the Office of Construction. An orientation and training of designers should be performed to acquaint the users with the system's capabilities. A detailed user's manual for set-up and use by county engineers, city engineers, and consultants should be developed. It is possible to supply the "run-time" version of the system on a periodic basis to those who will want access to the knowledge-base of the Department of Transportation. Using this media it is possible to keep and control the current standards used in design.

The system relies on construction knowledge to be supplied from the field and as such needs to be supplied with additional constructability considerations during the next construction season. The review system needs to be implemented with feedback on each proposal submitted. Assignment of the coordinating department needs to be addressed across functional areas within the Department of Transportation to determine the most effective area to assign the responsibility within the organization.

As users become more familiar with the system and the capability of the program it will be possible to add features to improve the productivity of the designer and their ability to access needed information. The software can be expanded to include expert systems for use as a decision support system. The program can be used as a design review tool through the addition of review checklists and routines.

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Appendix 1

Interview Guide

Constructability Survey Questions

Name: ______________________ Date: ______________

Firm: ______________________ Position: ______________

Phone: (   )   -

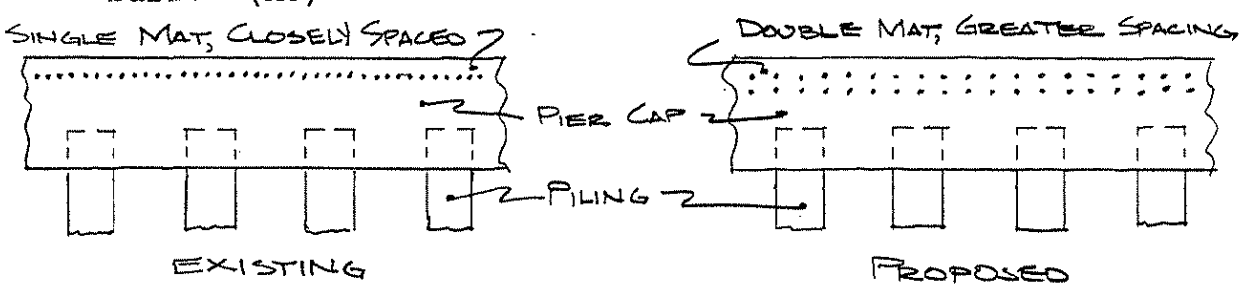
As you complete the questionnaire, please refer to Figure 1, Survey Configuration. Address each question on how it applies to individual bridge components as well as overall considerations. Please make any comments or suggestions that you may have.

Many of the following questions include one or more examples. At the end of each example, a code is given within parentheses. This code refers to Figure 1. For example, you may notice (B2c) designating: Superstructure - Deck - Steel Grid, Concrete Filled.

---

1. How can design details be configured to enable efficient construction? **Example:**

   Rebar spaced in the top mat of steel in a pier cap needs to allow for the proper placement and vibration of concrete. Increase bar size to decrease the total number of bars required or install an additional row of rebar "stacked" vertically thus increasing the total free space between bars. (A8)



2. What can be done in design to address simplicity, flexibility, sequencing, or substitutions? **Examples:**

   On dual or side-by-side bridges, the design should permit sufficient free space (eight inches) between structures allowing the barrier rail to be slipformed. (Currently, a two inch space is detailed.) (B4a and B4c)

   Another suggestion is to build one bridge versus two and construct a single, center median barrier. (C)

3. How is construction productivity improved when design elements are standardized? What details or components could be standardized thus enhancing construction activities? **Examples:**

   Presently, "crash wall" construction utilizes a transition from a round column shape to a flat wall structure. In each individual situation, a different size column, wall, and transition is detailed. Standardizing this shape and detail would facilitate the purchase of reusable formwork. (A7a)

   Concrete column dimensions should be detailed the same from pier-to-pier within a project and for all columns within a pier. This facilitates the use of typical column formwork. (A7a and A7b)

4. Which types of design details require more time and human resources to install? **Examples:**

   Unique connections that minimize structural steel materials should be avoided. Standardize connections (bolt sizes) to facilitate construction. (C)

   Detail welded shop and field bolted connections to increase construction efficiency. (C)

   Secondary structural connections should be specified as welded or bolted at the option of constructor/fabricator. (C and D)

5. What can be done with project specifications to promote construction efficiency? **Examples:**

   Coordinate specification requirements and drawing details. Items should be addressed in only one location in the specifications. (C and D)

   If component installation is to be in accordance with a code, specify particulars of that code which apply. (C and D)

6. When can the use of module/preassembly concepts facilitate fabrication, transportation, and installation of components during construction? **Example:**

Utilizing precast concrete deck panels as stay-in-place forms for the construction of precast concrete beam bridges saves construction time and improves project safety. (B2b)

7. How can access of personnel, material, and equipment be improved through design? **Example:**

Provide the contractor with a set of standards illustrating spacing, transitions, shoulders, dividers, and locations of traffic flow and control requirements. The contractor can use these standards to develop a traffic control plan that merges project construction requirements with safety and public user needs. (E and F)

8. What should be considered to provide sufficient construction access and staging areas? **Example:**

The design of the beams/girders and deck systems should consider how they may be used to facilitate scaffolding during construction. (B1 and B2)

9. What process is necessary in development of the contract plans and specifications to insure completeness? **Example:**

Construction joints on the contract plans should be clearly labeled as mandatory when required. If not thus marked, the construction joint is at the contractor's option. (C and D)

10. What elements used during construction inspection would facilitate field construction operations? **Examples:**

Soil and/or concrete tests are performed at specified intervals during construction activities. Do testing requirements expedite construction. (D)

The administrative process used for permanent material submittals should be clearly and concisely stated in the project specifications. This should include the individual responsible for review, his/her location, review time required, and documents needed for adequate review. (D)

11. What specific material requirements or specifications could be improved? **Examples:**

Vertical concrete surfaces require a designated time period before form removal. Due to advancements in concrete materials, this time period should be shortened. (D)

Shop versus field painted coatings should be addressed to minimize field work. (C and D)

Engineered coating systems should specify time requirements between coats in view of variable weather conditions. (C and D)

12. The integration of permanent components and embedments could be simplified in what ways? **Example:**

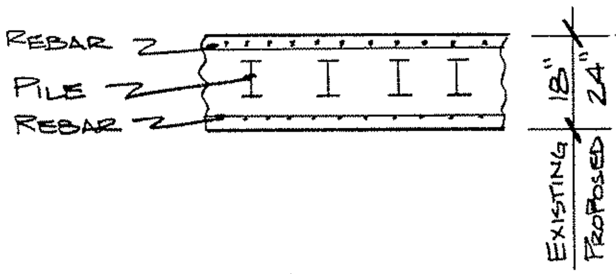
The installation of beam bearing pads and anchor bolts may be simplified by first "blocking out" the anchor bolt holes. After pier cap and beam seat concrete placement, set bearing pad with anchor bolts into blockouts at the required grade. Place high-strength grout around bolts and between the top of beam seat and the bottom of bearing pad. This technique insures that the anchor bolts are installed in the proper location and at the correct grade. (A9)

13. How do fabrication specifications and requirements affect construction activities? **Example:**

Careful attention should be given to fabrication and erection tolerances where tolerance should be permitted in one direction only. Expansion joint blockouts and tolerance may need to be adjusted due to weather conditions at time of installation. (B6, C, and D)

14. How can substructure considerations be improved to promote construction efficiency? **Example:**

Steel pile bent foundations encased in concrete with a mat of rebar on each face are designed with an overall concrete thickness of 18". The proper placement of concrete is difficult within this criteria. Increase the thickness to 24" to facilitate concrete placement. (A7)



15. What needs to be considered in the design of permanent reinforced concrete components to facilitate more efficient forming operations? **Examples:**

Combine blockouts where possible. Mechanical blockouts including piping, telephone, and electrical should be merged in one large blockout. Forming operations will be simplified. (C)

16. How can project safety be enhanced in the design process?
Example:

During staged bridge construction on the middle lanes, provide adequate project space for deceleration and acceleration distance into and out of the work area. Without ample space, access is difficult. The traveling public is endangered with construction traffic making quick stops into the work site and rapid starts out of the work site. (E)

17. What other ideas do you have, improvements that "only if 'they' would have thought of this during design," could improve construction performance?

Any questions?: Please write to the address below or call (515) 294-2045.

Please send to: Dr. Jim Rowings
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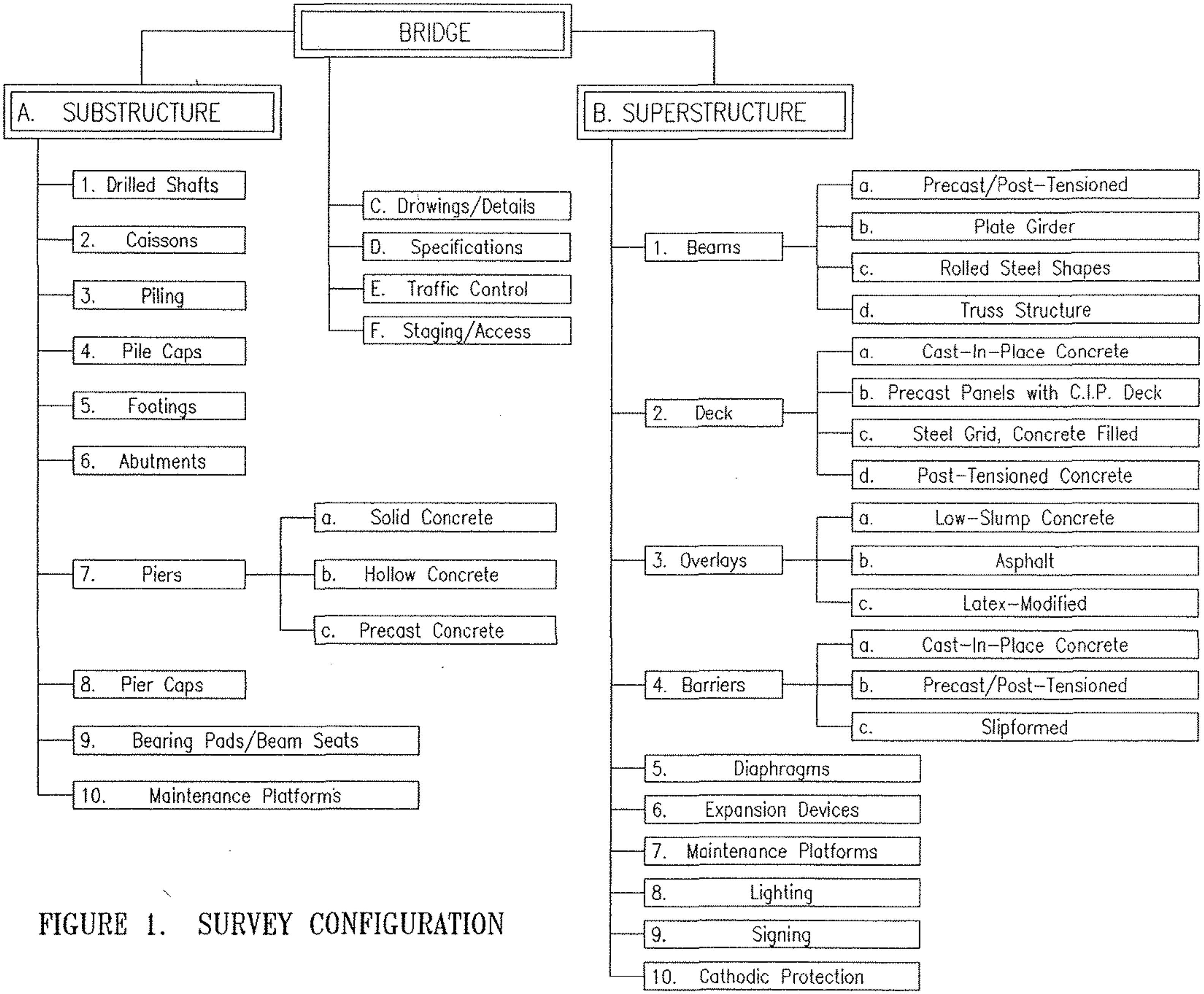

FIGURE 1. SURVEY CONFIGURATION

Appendix 2

USER'S MANUAL

Constructability Knowledgebase

User's Manual

Introduction

The knowledgebase is written with a Windows 3.0 development tool called KnowledgePro for Windows. Before the program can be installed Windows 3.0 and KnowledgePro for Windows must be installed. The user should also have a working knowledge of the Window's environment since many of the knowledgebase features parallel those found in Windows. It will also be the responsibility of the user to understand some of the operating features of KnowledgePro for Windows.

Installation

In its present form, the program expects to find all of the support files in the same directory in which it resides. This directory can be anywhere on the hard drive since you have to run it from inside of KnowledgePro for Windows. Therefore, to install the program, copy all of the provided files into an empty directory. The file naming convention is based on the file name extensions and is as follows:

.KB - Uncompiled knowledgebase

.CKB - Compiled knowledgebase

.BMP - Bitmap graphic files

.HYP - Hypertext files

.CUR - Cursor definition files

The main knowledgebase file for this program is BRIDGE.CKB. This is the compiled version, the file that should be used to activate the program. The uncompiled version, BRIDGE.KB, is the raw text file from which the compiled version was derived. Changes to the program can be made by altering this file and then recompiling it.

The .BMP files are the files by which graphics are stored for the program. Any graphic displayed on the screen must be a bitmap graphic file. For example, the graphics on the initial menu screen are all bitmaps.

All textual information in the program is stored in hypertext files, those with the .HYP extension. The contents and operation of these files will be discussed later.

The .CUR files are cursor definition files. The only one used in this program to date is the HAND.CUR cursor. This is the cursor in the shape of a hand that indicates hypertext or hyper regions in the program.

Running the Program

The program is started from KnowledgePro for windows either by running a compiled knowledgebase or by saying go to an uncompiled knowledgebase in the editor (see the KnowledgePro for Windows Reference Manual. The first screen presented to the user upon execution of the Bridge Constructability Knowledgebase (BRIDGE.CKB) is called the INDEX screen. The title is displayed at the top of the screen. This screen also becomes a sort of home screen that the user can always return to access a different thread of knowledge. The title changes with each screen to provide a cue to the user as to the name of the current screen. Along the top of the screen just below the title bar is a row of nine buttons. These buttons all have functions related to their name and can be activated by clicking on them with the mouse. The button's functions are as follows:

Index - Returns the user to the INDEX or initial screen.

Back - Displays the previous screen viewed.

Where - Opens a window and displays a list of titles of screens viewed prior to and including the current window. The Back button will always display the window directly above the last title on the list.

Reset - Returns the user to the INDEX screen and clears the Where list. This is just like starting the program initially.

Info - When viewing a constructability topic pressing this button open a window that provides information on the person that submitted the issue including the person's name, company, position, project description, location, and number, date, and the date entered into the system.

Direct - This opens a small window which prompts the user for the name of the topic he/she wishes to view. This provides direct access to the constructability topics, bypassing the normal menu selection process.

Print - This button will print the contents of the current window including and graphics.

Help - This provides an on-line hypertext help application similar is structure to the windows help.

Quit - This button terminates the current session.

The window can be iconized or the size can be changed. The buttons will remain the same size and wrap to the next line as necessary to accommodate a width less than the full screen. A scroll bar is provided along the right side to view topics that are longer in length than one screen. All of the functions mentioned so far are consistent to every screen in the knowledge-base.

Besides the title and the IDOT logo there are six graphics displayed on the INDEX screen. These graphics represent the six design areas containing constructability issues in the knowledge-base. Each of these graphics is a hyper-region. As the cursor passes over these regions it changes form the familiar arrow into a hand with the index finger raised as if to point. This indicates to the user that this is a hyper-region and that clicking on this area will activate the associated function. For example, clicking on the Substructure graphic will present a screen containing a subtopic relative to Substructure such as drilled shafts, piling, piers, etc. These items are presented in a list of hypertext segments. Clicking on any of the items in the list will then show another list of constructability concerns for that particular item. Choosing an item in the constructability concerns list will then present the constructability topic.

Adding to the Knowledgebase

Additions to the knowledgebase can fall into different categories, graphics and text files. Graphic files are simply bitmaps that you wish to display in a KnowledgePro window. The hypertext files control what is displayed in a window, how it is displayed, and where it is displayed.

Bitmaps

For this program, Paintbrush, as supplied with Microsoft Windows 3.0, was used to create the bitmap graphics. In the case of the graphics presented on the INDEX screen at the beginning of the program they were created entirely with Paintbrush. However, most of the graphics that the user wishes to add to the program will probably be created by scanning a portion of a document such as a drawing. How these scans are made into finished graphics that can be used in the program are largely determined by the scanner, the software used with the scanner, and the preferences of the user. The scanner and software used to date on this program cannot create a bitmap file directly. It can, however, create a .PBX file which is the default format for Paintbrush. Paintbrush in turn can create a bitmap form the .PBX file, and in this case provided a better graphics editor for cleaning up the files than the scanner software did.

The size of the graphics files can drastically affect the performance of the program. Large graphics will take considerably longer to load and display than smaller files. Things that have the greatest impact on the size of the graphic file are the actual area scanned in, the amount of reduction or enlargement, and the use of color. It is recommended that the use of color is limited to small graphic files whenever possible. Also use a graphics editor to trim away and unnecessary area around the important graphical information.

Hypertext Files

The easiest way to describe the function of hypertext is to show an example of a hypertext topic and then describe the components. The following is an example of the topic that displays the constructability concern for lower reinforcement mats in pile caps:

```
//lower reinforcement mat

    Placing the lower reinforcement mat below the ends of the piles (see graphic)
    requires that the mat be assembled around the piles. Designing the mat to be
    placed directly above the piles allows the mat to be pre-assembled and installed
    as a unit.

Related Topics: Specifications : #m2403.03.#m Proportions for Structural Concrete.

#cgraphic is load_bitmap ('ida.bmp'). bitmap (?graphic,20,10).
info gets ['John Pouge','Guetzko Construction','IX-218-7(72)--3P-07','Ansborough
Avenue','Blackhawk','Waterloo','May 15, 1990','October 18, 1990','Substructure','Pile
        Caps','Reinforcement','']. #c
#cwherei gets 'Lower Reinforcement Mat'. #c
#crelated_1 is ['spec.hyp','2403.03.'].#c
```

To reach this point in the knowledgebase the user would first select substructure from the INDEX screen, then select pile caps from the substructure screen, and finally select lower reinforcement mat from the pile cap screen. Whenever a piece of hypertext is activated with the mouse the knowledgebase looks for a match in the appropriate file. When it finds a match, lower reinforcement mat in this case, it reads in everything beginning with the // before the matching text to the next //.

Special control characters can be embedded into the text that is read in. Any text surrounded by #m becomes hypertext when it is displayed on the screen. On the line beginning with Related Topics:, the item #m2403.03.#m will be displayed as hypertext on the screen. Text enclosed inside the #c characters is compiled. This is a method by which code can be passed or added to the current knowledgebase.

The first line, #cgraphic is load_bitmap ('ida.bmp'). bitmap (?graphic,20,10)., loads the file ida.bmp into the topic graphic and then displays the graphic at column 20 and row 10. The next three lines pass a list of information to the topic info. This is used by the info function in the knowledgebase. The topic wherei receives the string 'Lower Reinforcement Mat' which is used by the where function to show the users position in the knowledgebase. The last line, #crelated_1 is ['spec.hyp','2403.03.'].#c is used to direct searches for the item 2403.03 to the correct file. The remaining text read in by the program is displayed on the screen. There are other special characters that can be added to the text to control color, fonts, and position of the displayed text. The user should refer to the KnowledgePro for Windows Reference Manual for information concerning the use of these characters.

Whenever a new item is added to any of the hypertext files it will need to have certain information in it. If a graphic is to be displayed it will need to loaded into a topic with a load_bitmap statement and then displayed with a bitmap statement. If a list is to be attached for the info topic it must conform to a specific format; ['submitter's name','submitter's company','project number','project city','date submitted','date added to knowledgebase','classification category 1','classification category 2','classification category 3','classification category 4']. The name of the called topic should be passed to the topic wherei. This maintains an accurate account of the current location in the knowledgebase. If there are one or more related items topics related_1, related_2, and related_3 will need information in the form ['hypertext file','hypertext item']. Calls to hypertext items that exist in the current hypertext file do not need to use the related topics. The only requirement is to enclose the hypertext string with #m characters, and that the enclose text matches a hypertext topic somewhere else in the file.

Information displayed on the screen should not be wider than the window in which it is displayed since a horizontal scroll bar is not provided by the program. However, items that are longer than the current display can be viewed by use of the vertical scroll bar shown on the right side of the window.