NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 390

Constructibility Review Process for Transportation Facilities

Transportation Research Board
National Research Council

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Report 390

Constructibility Review Process for Transportation Facilities

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Texas Transportation Institute
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Subject Areas

Planning and Administration
Highway and Facility Design
Bridges, Other Structures, Hydraulics, and Hydrology
Soils, Geology, and Foundations
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Highway Operations, Capacity, and Traffic Control

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation Research Board

This report describes the development of a process for assessing and improving highway-construction-project contract documents to ensure rational bids and to minimize problems during construction. The contents of this report are, therefore, of immediate interest not only to highway planners, facility designers, and construction personnel, but also to state and local government management and policy makers, consulting engineering firms, and highway construction contractors, all of whom can play a role in the process. The report's conclusions are based on experience in other fields of construction and on case studies of highway construction projects. Those case studies show that the constructibility review process can result in a benefit to cost ratio of 25 to 1.

Constructibility can be defined as the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives. Constructibility review is currently a milestone-driven and largely informal process, as usually practiced by state transportation agencies (STAs), and is given minimal attention during project planning and feasibility analysis. It is typically considered only informally during design reviews. This milestone-driven approach is a less than optimum strategy for implementing sound constructibility practices. Agencies seem to rely heavily on the construction expertise of design personnel, who are well versed in such technical issues as design standards and codes but may lack field expertise in construction methods and techniques. This limits the effective use of construction knowledge and experience during the planning stage and early in the design stage, when the ability to influence costs through changes in project plans and designs can have maximum effect.

Constructibility practices should be made an integral part of the project development processes. This integration can be ensured through formalization of constructibility review practices. Formalization will ensure that resources are available, the right expertise is involved, reviews are performed in a timely manner, and constructibility knowledge and experience are captured properly for easy retrieval later.

A companion publication generated during this research, *NCHRP Report Number 391,* "Constructibility Review Process for Transportation Facilities—Workbook," supports the process, developed in this report, for constructibility reviews that can be applied by STAs. The process consists of elements subdivided into increasing levels of detail. The workbook further details the functions, steps, actions, and tools essential to conduct a formal, comprehensive project-level Constructibility Review Process (CRP). Using information from the project development process, the CRP provides constructibility improvements that can be incorporated into planning and design documents. The CRP is presented in a generic format in the workbook and can be tailored to meet the characteristics of different project types and agency-level approaches.

Constructibility reviews have the potential to minimize the number and magnitude of changes, disputes, cost overruns, and delays during construction. In addition, there are intangible benefits that should considered. These benefits include higher productivity, better schedules and sequence of construction, enhanced quality, lower maintenance, safer jobs, and more safety and convenience for the traveling public. This report presents the logic, reasoning, and development for the formalization of the CRP for transportation facilities; the companion workbook provides the "how-to" details.

CONTENTS

ACKNOWLEDGMENTS

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Dr. Stuart D. Anderson (TTI) served as the principal investigator and Deborah J. Fisher as the co-principal investigator. Dr. Jeffrey S. Russell, a consultant to this research, provided timely input and review of all aspects of our research. We appreciate his involvement and commitment to this research.

This work could not have been accomplished without the dedication and persistence of several graduate research assistants associated with TTI and UNM. Specifically, the authors would like to thank Suhel Ruhman, Jennifer Livingston, Victor Inchausti, and Majed Limam for their efforts.

The authors wish to express their appreciation to all those who responded to questionnaires and to those agencies that participated in on-site interviews.

We particularly want to thank our Research Advisory Team. These individuals provided many hours of their time to help develop practical and useful constructibility implementation guidelines. This team included Mr. Hugh Thomas, Chief, Claims Resolution Branch, Caltrans; Mr. Jay Steele, Construction Engineer, Caltrans; Mr. Lauren Garduno, District Maintenance Engineer, Abilene District, Texas Department of Transportation; Mr. L.J. Vincik, Engineering Manager, Highway and Bridges, Brown & Root, Inc.; Mr. Travis Cannon, Vice President, Heavy/Highway Division, H.B. Zachry Co.; Mr. Roy Mendelsohn, Manager, Special Projects, Parsons Brinckerhoff Co.; Mr. Jim Wentworth, Chief, Advanced Research Team, Federal Highway Administration; and Ms. Clarisse Molad, Black & Veatch. Special thanks is given to Lauren Garduno for assisting the research team in developing two real life project examples for illustration in the workbook. We wish to also thank Mr. Dick Wright, Deputy State Engineer. His expertise in constructibility analysis for the Arizona Department of Transportation provided the research with first hand knowledge of the benefits and costs associated with constructibility reviews. Finally, we appreciate the comments on text material and the workbook layout and format provided by Mr. Rusty Haggard, our Technical Editor.

The authors would like to thank the NCHRP Panel and our Senior Program Officer Mr. Lloyd Crowther for their timely input, critical comments, and helpful suggestions as this research developed.

Constructibility Review Process for Transportation Facilities

SUMMARY

Transportation agencies recognize the need for contract documents that will ensure rational bids and minimize problems during construction. A significant aspect of developing high-quality contract documents is to incorporate a review process in the planning and design phases of a project to assess its constructibility. This process must include input from all professionals involved in planning, design, construction, operation, and maintenance of transportation facilities. Constructibility reviews have the potential to minimize the number and magnitude of changes, disputes, cost overruns, and delays during construction.

A successful constructibility review process for a state transportation agency (STA) must follow an established methodology similar to value engineering. The process must be flexible enough to be applied to all types of projects handled by STAs. Furthermore, the process must address the critical issues impacting today's transportation construction projects, such as ease of construction, enviornmental factors, construction phasing and scheduling, project safety, and accommodation of future maintenance and operations. To obtain maximum benefit from a constructibility review, it must be initiated early in the planning phase of a project and continued through design and construction.

The basic objective of this study was to develop a systematic approach and methodology for a constructibility review process (CRP). This methodology must incorporate constructibility concepts, existing analytical review tools, and functions needed to apply concepts and tools. Also, the methodology is designed to fit both different project characteristics and requirements. Finally, it must be adaptable to STA approaches to project development.

The report addresses this objective by describing the development of a formal, project-level CRP. Two main study phases were required to meet the objective. In the first phase, current practice of constructibility as applied to transportation projects was evaluated. Also identified were critical issues related to implementation of constructibility. On the basis of assessments of current practice and critical issues, a preliminary CRP framework and model were developed, using a structured process modeling technique. The second phase of the research fully developed the preliminary CRP. This effort included analyzing and applying the analytical review tools that support implementation. The CRP was documented in a user-friendly workbook. An implementation strategy was provided.

Constructibility requires a team approach and is mulidisciplinary in focus. Because of this, the research approach included an advisory team of industry practitioners. These practitioners represented STAs, consulting firms, construction firms, and a federal perspective. This Research Advisory Team met four times during the research. In addition, an ad-hoc member of this team was a constructibility engineer for one STA. The team's ideas and reviews of the CRP were instrumental in developing a practical process.

Current practice was assessed through two surveys and a set of interviews. Approximately 75 percent of STAs participated in the surveys. Also, 47 design firms and 32 construction firms responded to the first survey. Subsequently, five STAs and one design firm were interviewed. Results indicated that constructibility reviews are generally informal, milestone driven, and conducted during the design phase only. Agency-level support for constructibility was minimal in terms of program formality and mechanisms to encourage constructibility reviews. Implementation was impeded by a number of critical issues. Some significant issues included lack of feedback to designers, lack of timely and knowledgeable input from construction experts, poor communication among project participants, lack of clarity of plans and specifications, poorly documented construction phasing and sequencing, and availability of funds and personnel for reviews. Current practice and critical issues clearly supported the need for a formalized CRP.

The CRP was developed using a process modeling tool. With this tool, a framework of constructibility functions was identified for each of three phases of the project development process: (1) planning; (2) design; and (3) construction. For each constructibility function, specific information was modeled including inputs and outputs of the function, people and tools used in performing the function, and constraints that govern how the function is performed. Functions were then linked together based on the information flow between them. A preliminary framework and model was reviewed and approved. This model addressed problems associated with current practice and critical issues.

The CRP was further developed to incorporate steps and actions for each constructibility function. Tools needed to perform these steps and actions were developed and linked to each function they support. Twenty-one constructibility functions were included in the final model and supported by 27 review tools. These review tools were mostly paper based. However, some were computer based. Another 25 review tools were identified as advanced tools for the future application and described in an appendix of the workbook. The CRP framework and model was reviewed by four STAs and the Research Advisory Team. Two applications of the CRP were developed for actual projects of different size and complexity. Review and project applications provided evidence that the CRP was an effective tool for implementing project constructibility. Further, the model was flexible and could be applied to different project types. STAs can adapt the CRP to fit their project development process.

The major product of this study is the "Constructibility Review Process for Transportation Facilities—Workbook," published as *NCHRP Report 391* (*1*). The CRP workbook begins with an overview, primarily for senior policy makers, that explains the why's, what's, and how's of the CRP. Implementation guidelines, which constitute the major portion of the workbook, describe in detail each constructibility function and its steps, actions, and tools. Issues affecting how a step and action are carried out are identified. Finally, outcomes of each function are illustrated using two actual project applications that are integrated throughout the guidelines. In addition, the appendixes contain a glossary of terms, complete descriptions of tools in the workbook, and suggested future tools.

Through the assessment of current practice, critical issues, and the development of the CRP, it became apparent that certain paradigm shifts would be required to implement the CRP. These paradigm shifts are both project- and agency-level focused. Further, a benefit/cost analysis was developed based on constructibility reviews performed by a constructibility engineer from one STA. Results indicate that $25 in project saving can be achieved for every dollar spent on constructibility analysis.

An implementation plan was developed to aid STAs in formalizing constructibility on their projects and within their agency. Strategies include pilot projects and a team approach at the project level. Organizing for constructibility and lessons-learned system development were two agency-level strategies. Several research strategies were proposed to support the knowledge transfer process. Finally, the report provides specific conclusions relevant to the CRP and future research opportunities to enhance the CRP over time.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

BACKGROUND

Transportation agencies recognize the need for contract documents that will ensure rational bids and minimize problems during the construction of facilities. A significant aspect of developing high-quality contract documents is to incorporate a review process in the planning and design phases to assess a project's constructibility. This process must include input from all professionals involved in planning, design, construction, operation, and maintenance of transportation facilities. Constructibility reviews have the potential to minimize the number and magnitude of changes, disputes, cost overruns, and delays during construction.

Constructibility has been defined in a number of ways. Constructibility is the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives (*2*). Constructibility is also defined as a measure of the ease or expediency with which a facility can be constructed (*3*). Finally, constructibility is often portrayed as integrating construction knowledge, resources, technology, and experience into the engineering and design of a project (*4*).

It is generally agreed that the maximum benefits of constructibility occur if the process is formalized and started at the inception of a project. Conceptually, the maximum benefits are measured by the ability to influence cost with the highest influence occurring during the planning phase of a project, as shown in Figure 1. It is during the early project phases that key decisions are made and changes are implemented with minimum difficulty. These decisions, if made in a timely manner, can result in maximum savings to the project.

Quantifiable benefits from early implementation of constructibility programs have been documented on projects in the industrial and building construction industries (*5*). Most of these projects were large and executed on a cost reimbursable basis with design and construction often overlapped. This project delivery approach is not widely used in the transportation construction industry. Thus, the challenge is to develop a constructibility review process (CRP) that can be implemented in a project environment typically characterized by the design-bid-build approach, where construction is performed on a fixed unit price basis and competitively bid.

RESEARCH PROBLEM

A successful constructibility review process for an STA must follow an established methodology similar to value engineering (VE). The process must be flexible enough to apply to all types of projects handled by the agency. Furthermore, the process must address the critical issues impacting today's transportation construction projects, such as ease of construction, environmental factors, construction phasing and scheduling, project safety, and accommodation of future maintenance and operations. To obtain maximum benefit from a constructibility review, it must be initiated early in the planning phase of the project and continue through design and construction.

The research problem was to define an appropriate CRP for transportation facilities. A methodology was developed, and the proper use of professionals and analytical review tools was determined. The solution to this problem enables STAs to assess the applicability of construction reviews and provide guidance for implementation.

RESEARCH OBJECTIVE

The objective of this research was to develop a methodology for CRP for use by STAs. This methodology incorporated constructibility concepts, existing analytical tools, and functions needed to apply concepts and tools. This methodology was designed to fit both different project characteristics and requirements and approaches to project development followed by STAs.

Based on this objective, the major goals of the study were to (1) compile pertinent data on approaches to constructibility based on existing literature and current practice; (2) synthesize the literature and current practice to determine critical issues; (3) develop a conceptual framework to model the CRP that not only incorporates current practice but provides innovative administration guidelines STAs can use for implementation; (4) suggest analytical tools, both beginning and advanced, that can improve the process and identify when, where, and how these tools can be integrated into constructibility reviews; (5) develop a formal, comprehensive project-level CRP that can be adapted by STAs and implemented on different types of projects; and (6) suggest an implementation plan for transferring the knowledge to STAs.

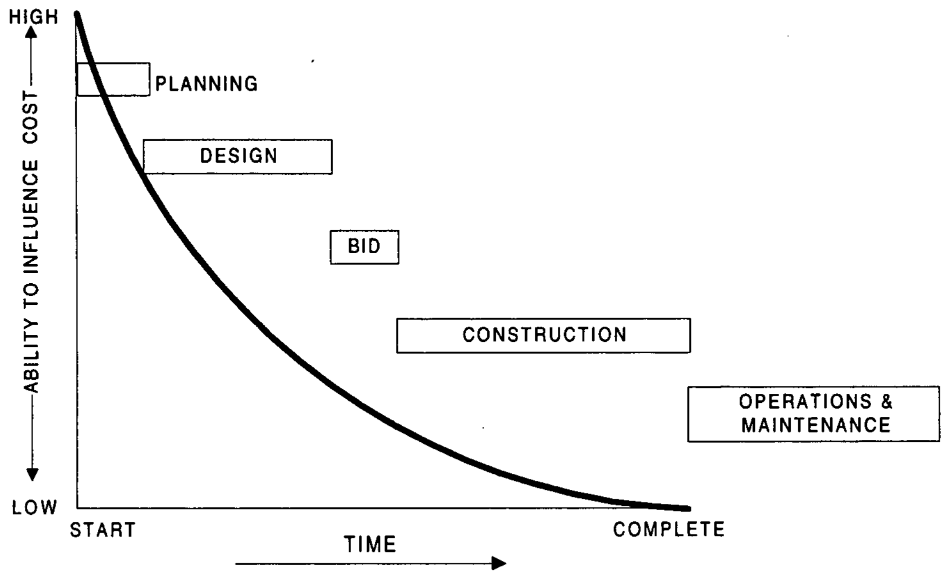

Figure 1. Ability to influence project cost.

These six goals were accomplished through the research approach discussed in the next section.

RESEARCH APPROACH

Because the proper implementation of constructibility requires input from many different professionals, the research approach incorporated a vehicle to obtain a similar spectrum of different viewpoints. A Research Advisory Team was formed to provide input. This team met four times during the research to review and comment on different aspects of the research. It also provided input through review of various documents as the constructibility review process developed. The team was composed of the following:

State Agencies—Caltrans and Texas Department of Transportation
Contractors—H.B. Zachry Co. and Brown & Root, Inc.
Design/Consulting Engineers—Parsons Brinckerhoff, Black & Veatch, Inc.; and Brown & Root, Inc.
Government Agency—Federal Highway Administration

Further, expertise was provided by a consultant involved with constructibility research for both private industry and a state agency. Finally, a Constructibility Engineer, with the Arizona Department of Transportation, also provided significant insights into constructibility reviews and benefit/costs of these reviews.

The research was conducted in two major phases. The first phase determined current practice of constructibility as applied to transportation projects, identified critical issues related to implementation and developed a preliminary CRP framework. The second phase of the research fully developed the preliminary CRP. This development effort included the analysis and application of analytical review tools that support implementation. The CRP was documented in a user-friendly workbook. An implementation strategy was also provided as part of the second phase of the research.

Current Practice

Current practice, including program formality and use of review tools, was assessed through literature review, two questionnaires, interviews with transportation agencies, and input from the Research Advisory Team. An extensive literature search covered constructibility practices in both the transportation industry and nontransportation-related industries. Most formalized constructibility processes have been developed by the private sector for industrial or building design and construction projects. A few state agencies are attempting to formalize this practice. Literature relevant to constructibility review tools exposed many different tools available for this purpose. Analytical tools can be advanced computer based but noncomputer-based beginning tools are also being extensively used.

Two surveys were used to capture current practice. The Part I survey was a one-page questionnaire. This questionnaire was sent to each STA. Each agency was also asked to send a second one-page questionnaire to design and construction contractors currently performing work for them. The purpose of these questionnaires was to capture information regarding the formality of current constructibility practices, level of constructibility input during major project development phases, and critical issues impacting implementation.

For the Part II survey, a questionnaire was distributed to all STAs to collect information on each agency's organizational environment with regard to current project development practices, selective uses of constructibility in project development, and application of related programs, such as total quality management (TQM). This questionnaire also collected indicators of the level and type of computer use within agencies and computer use specific to support constructibility. The Part II survey provided background information on general agency characteristics and practices that are helpful in developing a generic constructibility review process. Indicators of computing technology aided in evaluating the capability state agencies have to implement existing analytical review tools.

Five STAs and one design firm were interviewed. The primary focus of these interviews was to examine and understand specific constructibility practices and the integration of these practices into project development phases. This information was essential for developing the preliminary CRP framework.

Critical Issues

The Part I questionnaire identified critical issues relevant to implementation of constructibility from the perspective of STAs, design firms, and construction firms. Respondents were requested to list three issues pertinent to implementing constructibility. All issues were first analyzed and then categorized by similar problem areas. The number of times a general issue was cited was then recorded in terms of both frequency and percent of all responses. This analysis was performed for each of the three perspectives.

Critical issues reported in response to this questionnaire were, without exception, issues that would impede or act as barriers to the CRP in the view of STAs, design firms, and construction firms. Issues were stated with particular reference to their impact on the various phases or functions of project development. Additional agency-level issues were identified through the Part II questionnaire and interviews, the review of literature, as well as from observations of the Research Advisory Team.

Preliminary Constructibility Review Process Model

A composite evaluation of current practice and critical issues served as a basis for developing a formal CRP framework. A structured modeling technique was used to identify major functions performed during a project CRP. These functions were linked to three major project development phases: (1) planning; (2) design; and (3) construction. Inputs and outputs for each function were identified and defined. Constraints, implementation tools, and people involved in function performance were also identified. Key information interfaces between the CRP and project development phases were determined and documented. This preliminary CRP framework was the basis or background structure for developing a formal, comprehensive project-level CRP during Phase II of the research, including the use of review tools and other implementation techniques.

Formal Constructibility Review Process Model

The formal CRP was developed through interviews with STAs and other potential users. Key inputs were received from the Research Advisory Team, and modifications were made as appropriate. Information about each component of the CRP was developed in detail. The details were then converted into a user-friendly format describing constructibility functions via steps, actions, and tools associated with each function. General guidance as to how functions were performed under different project scenarios was illustrated through the application of two actual projects. This information is described in the CRP workbook (*1*).

Certain changes are needed to effectively implement the CRP. Areas of change, signified as "paradigm shifts," are required at both the project and agency levels. These paradigm shifts are discussed in some detail as they relate to critical issues and barriers to implementation. One such barrier is the up-front allocation of scarce resources—time, money, and people. Strong evidence indicates that constructibility reviews pay for themselves by reducing project cost.

Constructibility Review Tools

A comprehensive review of literature and existing constructibility practices provided the basis for identification and development of analytical review tools for use in the CRP. A total of 52 tools was identified. Tools were classified in relation to the CRP by whether or not they are used to understand/communicate constructibility; to implement/measure constructibility; or if they are cutting-edge technology/computer tools. Integration of tools into the CRP was accomplished by linking a tool(s) to each constructibility function of the review process. On the basis of input from the Research Advisory Team, 27 tools were selected and integrated into the CRP workbook guidelines. The workbook uses tables, flow charts, and graphics to communicate these tool concepts.

Detailed descriptions of each tool were developed and incorporated into the workbook Appendix B. This appendix contains two parts: Part I describes 27 tools that are used in the body of the workbook guidelines. Part II identifies 25 review tools for future use as the CRP is implemented. These "future" tools would be considered only by an agency that already has a well-established, formalized CRP. Appendix B also includes a comprehensive bibliography of additional information about specific tools. Roadmaps are used in the appendix to indicate where (which constructibility function) tools should be applied in the CRP and citations for those tools.

Implementation Plan

Strategies for implementation were suggested. These strategies considered paradigm shifts required of transportation agencies to formalize the CRP. Typical steps for an implementation strategy were then developed. Specific steps included recognize need; develop tools; market tools; and transfer knowledge. Both project- and agency-level approaches to knowledge transfer were incorporated into the steps. Resources associated with different strategies were estimated.

Summary

Conclusions were developed with respect to an assessment of the CRP and its potential. Areas covered include critical success factors, pilot projects, and full-scale implementation. Future research might include case studies, technology enhancements, and continuous improvement initiatives.

CHAPTER 2

CURRENT PRACTICE IN CONSTRUCTIBILITY

INTRODUCTION

This chapter presents findings in relation to current practices involved in implementing constructibility. Literature was studied to determine the extent to which constructibility practices have been documented and to identify tools that support these practices. Survey techniques were used to collect relevant information and data from STAs, design firms, and construction firms. Interviews provided additional insights into constructibility practices and their use in different project development phases.

LITERATURE REVIEW

A comprehensive review of constructibility-related literature was conducted by Russell and Swiggum (*6*). This literature review covered six categories of publications and was documented in an annotated bibliography. The six categories were (1) identifying the need for constructibility; (2) guidance on constructibility improvement and/or implementation; (3) specific applications related to constructibility including previous case studies; (4) case studies of constructibility used on previous projects; (5) expert systems that can be used to enhance constructibility; and (6) contractual issues regarding constructibility. Literature applicable to the highway sector was found to be particularly scarce. Pertinent articles identified by Russell and Swiggum were reviewed in detail. In addition, a TRIS literature search was performed to locate more recently published articles. Very few new articles were found beyond those covered by Russell and Swiggum. A summary of these new articles follows.

Research conducted by the Construction Industry Institute (CII) has been the driving force behind the formalization of constructibility. Initial CII research identified many specific constructibility ideas. This large number of ideas was reduced to 13 constructibility concepts (*2*). Four additional concepts were added to the original 13. The CII also developed a *Constructibility Concepts File* that provides helpful examples related to the application of each concept (*7*). The concepts were organized by three major project delivery phases: (1) conceptual planning, (2) design and procurement, and (3) field operations. Most of these concepts were developed from private industry and, primarily, the industrial construction sector. Their applicability to transportation projects must be assessed individually.

A second major constructibility research thrust by CII produced a comprehensive *Constructability Implementation Guide* (*5*). The guide provided a methodology for implementation in the form of a roadmap, as shown in Figure 2. A comprehensive explanation of each component of the roadmap was provided. Nineteen constructibility implementation tools were offered that aid in developing and sustaining effective constructibility programs. The tools contain barrier assessment forms, concept application matrices, suggested policy statements, and so forth. Case studies of successful project constructibility programs were also included. Quantified costs and benefits were discussed. This document provides excellent background information for developing the CRP for transportation facilities, including tool applications.

While constructibility has been studied in the transportation industry, its exposure has not been as widespread as in the industrial and building construction industries. A first major constructibility effort was a *Highway Construct*Ability Guide* developed for the Texas DOT (*3*). This guide described constructibility in some detail with respect to its definition, relationship to other programs, such as value engineering, why and when to pursue constructibility, and factors affecting highway constructibility. It also offered a constructibility enhancement program. This program identified specific objectives, and offered two tools for implementation, case history examples, and program implementation barriers. One tool was the Hierarchy of Objectives technique for hierarchically modeling constructibility objectives. The other tool was a Highway Constructibility Knowledge Base. This knowledge base was an organized collection of ideas related to examples of applications or solutions to highway construction constraints. The guide contained many useful ideas but lacked a structured process with clearly defined steps for implementing constructibility.

A second major constructibility study was conducted for the Florida DOT (*8*). The constructibility review system developed for FDOT consisted of two parts: (1) constructibility review and (2) post-construction review. The system suggested that constructibility reviews should be performed at 30, 60, 90, and 100 percent completion of design. A second major review should occur after construction is completed. Both review processes addressed various elements of construction and their associated problems. Checklists have been developed. Common problems encountered on FDOT projects were also provided with suggested improvements and lessons learned. An outline of a database

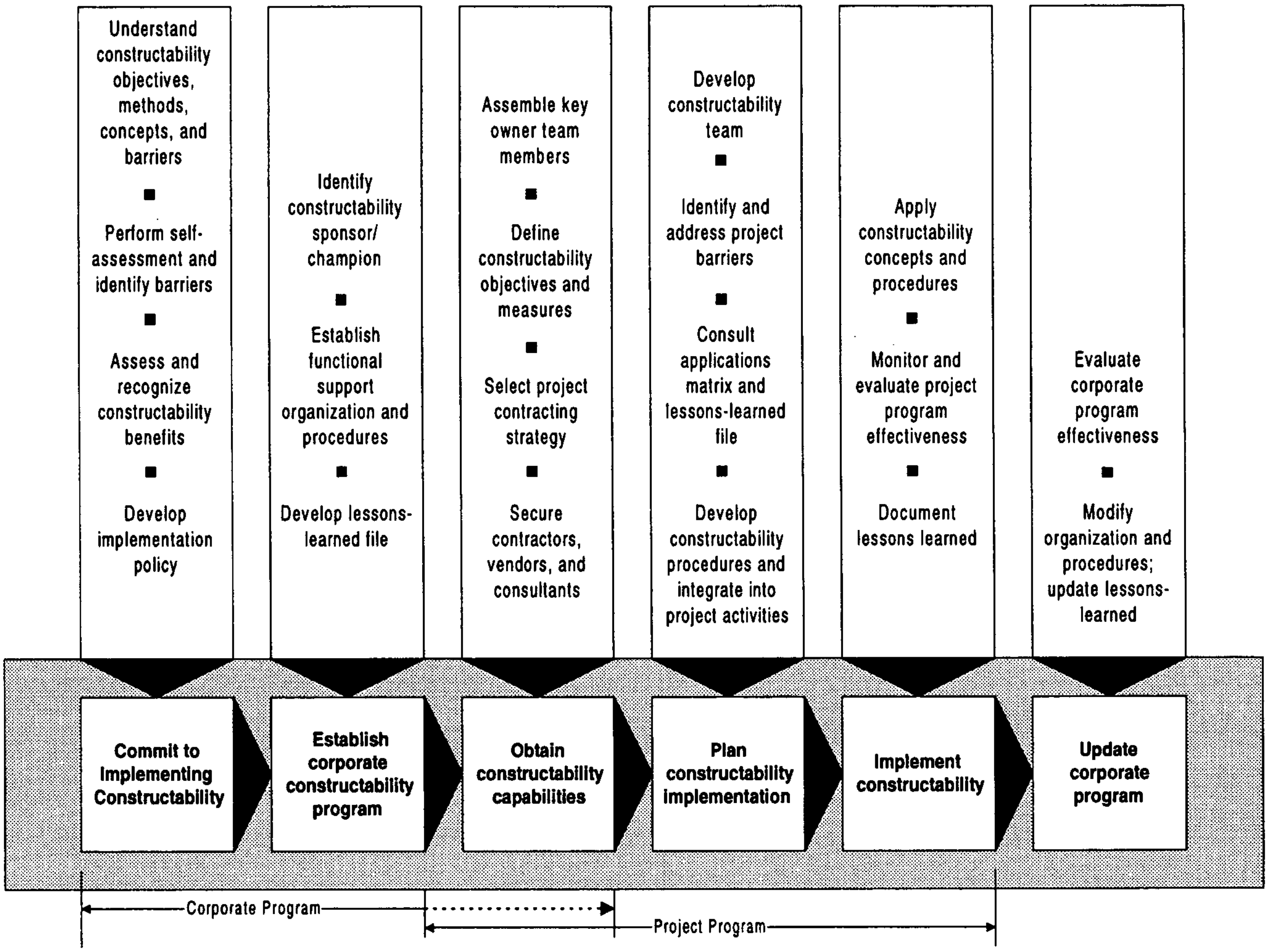

Figure 2. Constructibility implementation roadmap (5).

structure for collecting constructibility information was provided.

A *Constructibility Guide* was developed for the Arizona DOT (*9*). This guide provided an overview of constructibility and identified current practices. In the area of implementation, goals and objectives were defined and a general philosophy was provided to aid ADOT in incorporating constructibility into their project development process. A team approach was suggested. A major contribution of the guide was the identification of numerous constructibility concepts. These concepts were organized by categories of construction work, maintenance and operations, and general areas. The concepts were supported by checklists. This comprehensive list of concepts and associated checklists was useful in developing details of the CRP described in this report.

Russell and Swiggum developed a "Highway Constructibility Work Process" for Wisconsin DOT (*10*). As shown in Figure 3, the process was divided into two phases: (1) pre-contract award constructibility; and (2) post-contract award constructibility. Each phase has a number of specific steps, which are described in detail. The pre-contract award stage is linked to project planning and design while the post-contract award phase relates to project construction. Twenty-seven different tools are presented that aid implementation. One tool shows specific points in the WisDOT project development process where other tools should be used. A case study application of the process is described. This comprehensive approach served as a major basis for development of the CRP framework for this research.

Advancements in computer technology are now making hardware and software products available that can improve and automate the management of constructibility practices. These new technologies have the potential to reduce costs and improve schedules by providing decision makers with improved information for planning, design, and construction. Computers may also be used to make consistently formatted information available to all project participants, as well as personnel from other projects. The following discussion documents constructibility-related computer systems. References found describe several developed or in-progress computer systems that directly or indirectly facilitate constructibility gains with proper implementation. This literature review is divided into the following categories by type of tool: (1) hypermedia/multimedia; (2) 3-D CAD/animation/virtual reality; (3) expert systems/database systems; (4)

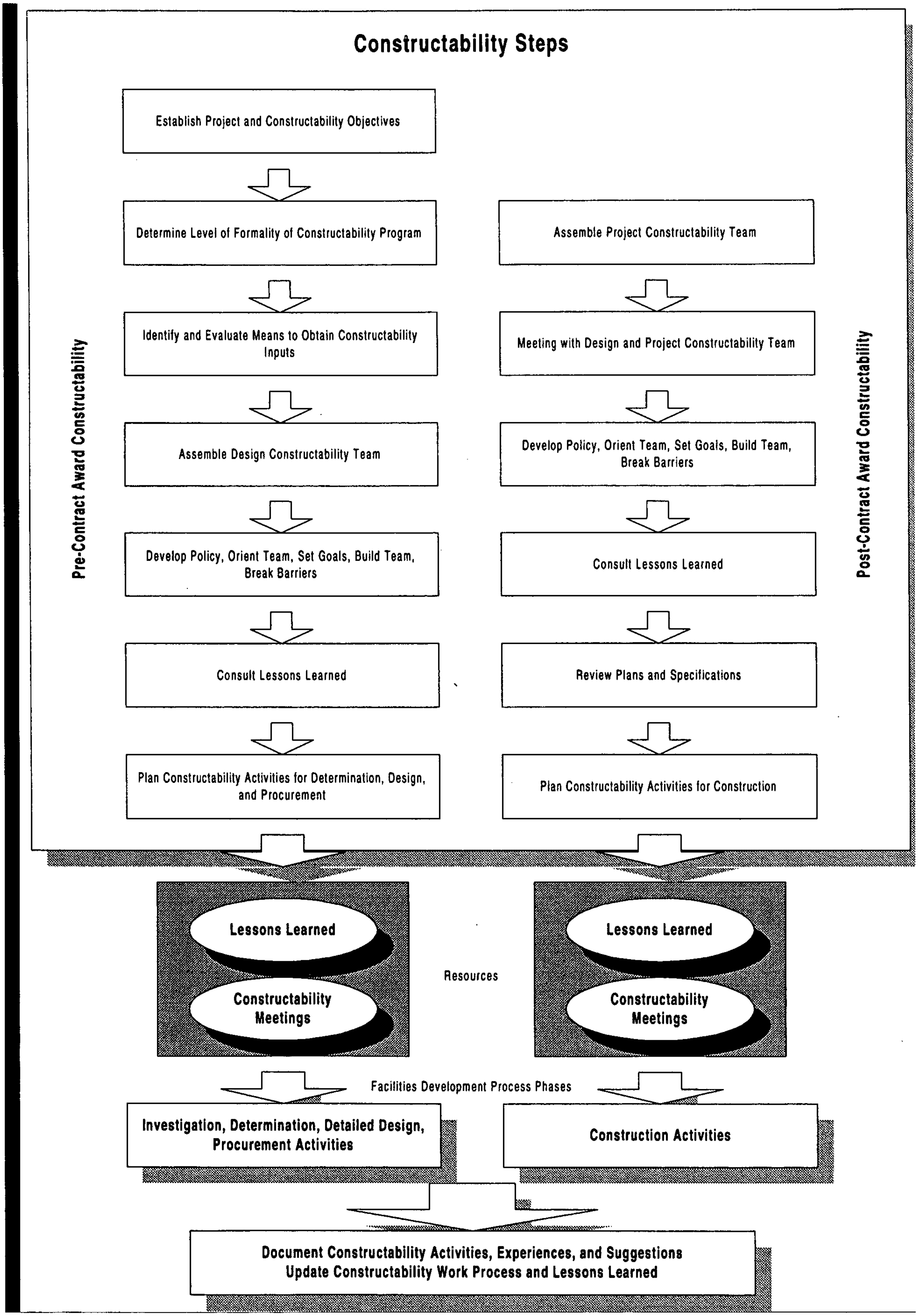

Figure 3. WisDOT's constructibility work process (10).

process modeling; and (5) GIS/graphical modeling/digital imaging.

Research conducted in the area of the application of multimedia to constructibility has been performed by McCullouch and Patty (*11*). The different media forms used in this computer tool are text, graphics, audio, and motion video. The system has four windows, with each window performing a specific function in the constructibility process. In addition, Vanegas has developed an Integrated Multimedia System for Constructibility Lessons Learned (IMSCL2) that provides project managers a means to acquire, store, retrieve, and manipulate constructibility lessons learned (*12*). The system contains five modules; the first two capture and process images and audio data. This information is then used to develop an electronic constructibility manual in module 3. Module 4 provides three types of interaction between the system and users from the teams involved in the project. Module 5 offers different mechanisms for displaying the digitized images or manuals. Williams takes a more general approach to multimedia, discussing the stages of emerging technologies that can be applied to construction (*13*).

The new technology of virtual reality (VR) provides a revolutionary way to improve the interface between the human operator to the computer, by removing the distinction between the system and the user's environment. This is accomplished by immersing the user in an artificial world, using computer graphics and 3-D images. Minakuchi, Morita, and Futagami presented a 3-D modeling method with a stereo-scope display and a 3-D input device, which are elemental technologies of virtual reality (*14*). Robinson presents 3-D computer modeling and animation tools that are increasingly being used in design and constructibility reviews (*15*).

Expert systems and database systems, if properly applied, could result in substantial constructibility gains. Lack of personnel, the inability to fill the knowledge void caused by transfer or retirement of experts in the field, and the inability to effectively learn from past mistakes were some of the factors that indicate a need for advanced automation techniques in this area. Wentworth and Knaus presented a brief overview of two ongoing expert system research projects and future directions for research and development at the FHWA (*16*). The following is a list of specific systems developed that relate directly to constructibility or to highway research in general:

1. Lee et al. developed *HCIS,* which is a bank of knowledge developed from past construction experiences obtained mainly from change orders (*17*). Accessing this knowledge could prevent problems encountered on past projects from reoccurring on future projects.
2. Goel discussed steps an organization should take to develop a custom *Lessons Learned Best Practice (LLBP)* database for managing constructibility lessons learned (*18*). He also discussed how to overcome barriers to developing and implementing such a system.
3. Rajan developed a three-module system for constructibility analysis of work-zone traffic control planning that includes a database module (*CONTRAF*), an expert system module (*TRAPS*), and a fuzzy scheduling module (*19*).
4. Ritchie et al. developed *SCEPTRE,* a knowledge-based expert system that assists highway engineers in planning cost-effective flexible pavement rehabilitation strategies at the project level (*20*).
5. Khan et al. developed *4RSCOPE*—a program developed to allow Caltrans engineers to gather data from both office records and field assessments—to determine design features to be included, hence determining the project scope for rehabilitation projects (*21*).
6. Faghri and Demetsky developed *TRANZ,* a prototype knowledge-based system developed for selecting appropriate traffic control strategies and management techniques around highway work zones in Virginia (*22*).
7. Linkenheld et al. developed a knowledge-based expert system for the phasing and signal timing of intersections called *PHAST* (*23*). The program takes intersection geometry and traffic volume as input and generates appropriate phase plan, cycle length, and green time for each phase.
8. Pikkarainen developed *RMPES,* which presents the current state of road and traffic conditions by calculating summaries of the road data bank (*24*). Future conditions are predicted using simulation models in which the control parameters are objectives set by the planner.
9. Kirrschfink (1994) developed a knowledge-based system, which determines traffic density data in Hamburg, Germany (*25*).
10. Russell and Swiggum present a framework to develop a simple and efficient lessons-learned database with examples (*10,26*).

Computer process modeling has the capability of describing the various steps of a process in detail, including timing, resources, and personnel involved (*27*). Process modeling also has the capability of documenting relationships among various steps. Sanvido and Norton developed a model of the building design process, called integrated design process model (IDPM), that helps designers better integrate activities (*28*). CII described pre-project planning using a process modeling tool (*29*).

A geographic information system (GIS) is hardware and software that stores, analyzes, and disseminates information about areas of the earth. Jeljeli et al. take the example of contractor pre-qualification and apply a GIS database as a mechanism for rapid retrieval and manipulation capabilities to satisfy the need of spatial and descriptive information required in the process (*30*). Oloufa et al. describe a GIS database that relates descriptive soil data to a display of corresponding locations of boreholes (*31*). The system uses a graphical user interface (GUI) to facilitate the input, query, and output of data, in addition to drawing borelogs. Smith and Rayner reviewed work accomplished toward the automation of as-built drawings using digital imaging processing (*32*). Krzaczek (1993) presented a new method for graphical modeling in 2D (*33*). This system recognizes drawings, using fuzzy set theory and expert systems, interprets inaccuracies, and generates numerical descriptions of the computational task.

The literature review provided background information on existing constructibility review models and basic tools used with these models. Other areas were identified where computing technology might provide a basis for developing analytical tools to support constructibility reviews. Tools specific to the constructibility review process developed in this research are discussed in Chapter 7.

PART I—SURVEY RESULTS

The Part I survey requested input from STAs and firms that perform agencies' design and construction. A one-page questionnaire was sent to each transportation agency. They were asked to respond to this questionnaire. Each agency was also asked to send a similar one-page questionnaire to three design firms and three construction firms. The purpose of these questionnaires was to capture information regarding the formality of current constructibility practices, level of constructibility input during major project development phases, and critical issues impacting implementation. Table 1 indicates the number of Part I questionnaires received from STAs, design firms, and construction firms. The transmittal letter, instructions, and one-page questionnaires are contained in Appendix A.

State Transportation Agencies

Of the 40 STAs responding to the Part I questionnaire, 23 percent have formal constructibility programs, as indicated in Figure 4. Of those agencies that stated that they had formal constructibility programs, five provided documentation of their programs. However, the level of formality of these programs varied. Several programs were very formal (Caltrans and Arizona) as they incorporate concepts suggested in the literature, such as specifying constructibility objectives, forming a constructibility team, determining level of formality, and mechanisms to obtain constructibility input. Several were less formal and incorporated constructibility into design through standard design procedures. These less formal programs often used checklists and defined points in the design process where reviews should take place. In general, all of these formal programs appeared to lack distinct functions or steps that lead the user through an implementation process. They were also heavily focused on the project design phase.

Most STAs that perform constructibility programs informally used similar approaches; some details differed according to project complexity and the degree of involvement of the agency with in-house design. Informal constructibility was accomplished through a series of review sessions at various stages in the project delivery process (e.g., 30, 60, and 90 percent design or other milestones). These reviews also occurred at final design, just prior to bid. Agencies seem to rely heavily on the construction experience of design personnel, and in some cases, construction personnel. Checklists were frequently used to ensure critical issues were covered. Meetings were also mentioned as a key mechanism for obtaining a broad range of input on construction-related issues.

Figure 5 summarizes the average level of constructibility input by major project phases. As indicated, the level of constructibility input is lowest during the planning phase and increases somewhat during each of the next two phases. This relationship is diametrically opposed to what the published literature states, that is, constructibility should begin early and have a high level of involvement first in planning and then in design.

The data were separated into three groups, according to the percent of in-house design performed by STAs. These groups were:

- High in-house design (range 60 to 100 percent—average 82 percent)
- Medium in-house design (range 40 to 60 percent—average 55 percent)
- Low in-house design (range 0 to 40 percent—average 24 percent)

Figure 6 recaps the distribution of respondents in each group. Forty-nine percent of STAs performed the majority of their design work in-house. About 28 percent of them contracted their design work to outside consultants or design firms. The ratio of in-house to out-sourced design has remained constant over the past 3 years.

TABLE 1 Distribution and receipt of Phase I questionnaires

Group	Sent Out	Received	Response Rate (%)
Agency	52	40	77
Design Firm	156	73	47
Construction Firm	156	50	32

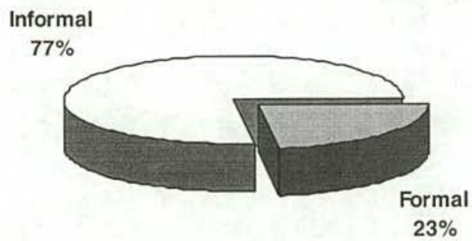

Figure 4. STA formal versus informal constructibility programs.

Analysis of the CRP by level of in-house design revealed very little difference in current practice. This may be a reflection of the informal review-driven nature of constructibility as presently practiced. Constructibility reviews occur at predetermined milestone points during design, regardless of whether or not design is performed in-house or contracted out. Personal interviews with several STAs confirmed this conclusion. Furthermore, according to the design firm survey data, design firms interact with state agency personnel on constructibility issues at stipulated points during design. This coincides with STA approaches and viewpoints.

Design Firms

Seventy-three responses were received from design firms, as shown in Table 1. Sixteen percent of these firms stated they had a formal constructibility program, as shown in Figure 7. Similar to STAs, the degree of formality varied from extremely well documented with flowcharts and definitive procedures to checklists that ensure design standards were met and construction issues were considered when reviewing plans. However, most design firms that practiced constructibility did so informally through traditional and periodic reviews. These reviews were frequently performed by senior design personnel and project managers. Interaction with agency personnel occurred at major predetermined milestones. On more complex projects, construction participation was often obtained through outside sources. Contractor involvement increased just prior to start of construction.

Construction Firms

Fifty responses were received from construction firms (see Table 1). None of these firms had a formal program for constructibility. Most indicated that they pursue constructibility as part of preconstruction planning and bid preparation. Senior personnel were involved in the review process. Interaction with design or agency personnel was a common approach; however, this normally occurred just prior to start of construction. Some contractors used value engineering and participated in partnering programs to enhance the constructibility of their projects.

PART II—AGENCY PRACTICE AND COMPUTER USE

Part II of the current practice survey included a questionnaire that was distributed to all STAs. This questionnaire was designed to collect information on each agency's organizational environment, with regard to current project development practices, selective uses of constructibility in project development, and application of related programs such as TQM. The Part II questionnaires also collected indicators of the level and type of computer use within agencies and computer use specific to support constructibility. The goal of this questionnaire was to provide background information on general agency characteristics and practices that were helpful in developing the CRP framework. Indicators of computing technology aided in evaluating the capability state agencies have in order to implement existing analytical review tools.

Fifty-two Part II questionnaires were mailed to STAs. Thirty-nine questionnaires were received. This reflected a 75 percent response rate. The transmittal letter, instructions, and complete questionnaire are contained in Appendix A. The

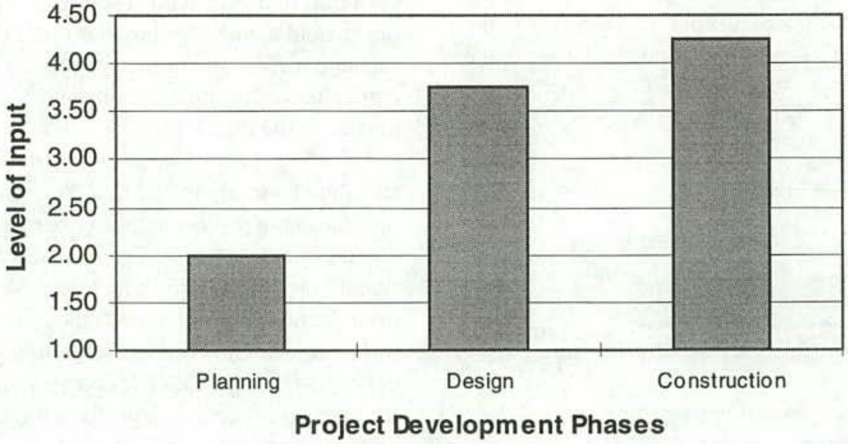

Figure 5. Level of constructibility input at different phases (1—minimum, 5—maximum).

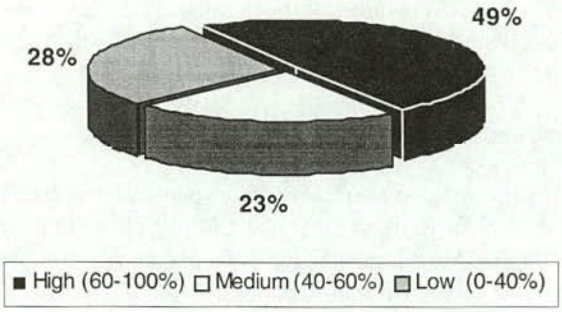

Figure 6. Percentage of STAs performing in each range of in-house design.

discussion that follows represents the analysis and findings from each section of the survey.

Agency-Level Information and Constructibility

Several questions focused on constructibility-related issues. As shown in Figure 8, 14 percent of the agencies stated they use contract clauses to ensure that design firms incorporate constructibility when design was contracted. However, those that provided example contract clauses actually provided general condition clauses stipulating that plans and specifications should be reviewed and checked for completeness. In other words, there was no specific contract language referring to constructibility. Constructibility was simply thought of as being performed through periodic review practices. This reflected the common notion that reviews identified and solved constructibility problems.

For those state agencies that did not use contract clauses to ensure that design firms implement constructibility, most stated that constructibility analyses were performed periodically through a review process. This was consistent with findings from the Part I survey. It was interesting that no mention was made of selecting a design firm that had a constructibility program in place. This was again consistent with the Part I survey, as most design firms had informal programs and interfaced with STAs through predetermined design reviews. The use of contract clauses may be a tool to help agencies obtain better constructibility reviews from their design contractors. The CII provided example clauses in their guidelines (*5*).

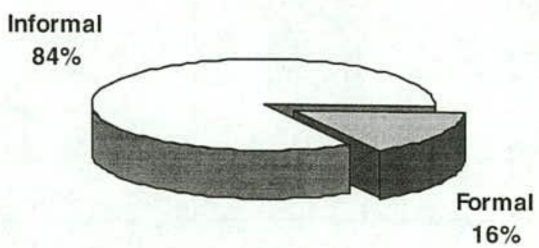

Figure 7. Design firms' formal versus informal constructibility programs.

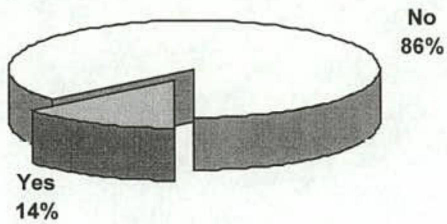

Figure 8. Use of contract clauses to implement constructibility.

Of particular interest was the overall response to the Part II survey indicating the percentages of work among agencies managed at the central, or home office, compared with work that is managed in decentralized, or field offices. The percentages of work managed at the central office in terms of planning, design, and construction were 77, 62, and 13 percent, respectively. It is obvious that, for the most part, planning and design were considered the province of the agency's home office, while construction was, and appropriately so, managed by field offices. These percentages changed somewhat in those states where the transportation facility program was large, and where there were large, well-developed field offices, such as in the Texas, California, and Florida state agencies. Their district/field offices had planning and design capability and authority to carry out their programs at the field level. It was generally assumed that the implementation of a formal CRP would be accomplished more effectively in those organizations in which planning and design were accomplished in a central office.

Respondents to the survey also indicated an almost universal, traditional project delivery approach of "design-bid-build" whereby each of these functions was contracted or performed separately. In three states (Alaska, California, and Colorado) there were responses indicating that between 1 and 5 percent of their projects were managed by a "design-build" approach that would involve a single firm with design and construction responsibility. Four states (Colorado, Delaware, Nebraska, and Texas) indicated that between 1 and 20 percent of their projects were managed by a "design-construction management-build" approach, involving a construction manager with responsibilities for interfacing with design and managing construction. This use of a construction manager offers an alternative project delivery approach that can enhance communications and constructibility among all parties to the process.

With regard to project organization, 25 STAs indicated that they were organized in a "matrix" fashion that involved the sharing of project authority between functional managers and a project manager. Ten other STAs maintained a "functional" organization in which functional managers and their organization's internal management hierarchy plan and control a project. Only one agency employed a "task force" project organization whereby a project manager had full authority over all aspects of a project. It is apparent that an active and conscientious "constructibility coordinator," in addition to a project manager, in a matrix or functional organization could promote constructibility among functional managers, as well as designers and constructors. A fully developed project organization, depending on program and project size and complexity, may conceivably utilize a project manager, a construction manager and a "constructibility coordinator" for most effective coordination and control of the project development process (PDP).

Another question of interest related to the number of state agencies that use outside consultants for constructibility reviews, when design was performed in-house. Only 4 percent of state agency projects used outside consultants. The use of outside consultants, such as construction managers, may be one solution to bridging the communication gap between design and construction, in addition to obtaining construction expertise and knowledge early in project development.

Most states have developed in recent years various programs to improve overall efficiency of their operations. As shown in Figure 9, 69 percent of STAs had a TQM program, 83 percent used a formal partnering concept, 89 percent had a VE program, and 69 percent used financial incentives. However, when asked to estimate the specific use and application of these programs on projects, only a small percentage of projects used them (typically 5 percent or less). Only in a few cases did respondents indicate that a connection existed between the application of such programs and any influence on constructibility.

These programs have, however, tended to cause the initiation of constructibility reviews in conjunction with their application. While several programs were relatively new (e.g., TQM and partnering), the results implied that a successful project-level model for each has not been developed. This lends support for developing a project-level CRP.

Thirty-nine percent of the respondents had a project development plan that was documented graphically. Nearly two-thirds of STAs did not have such a plan that describes their project development process in this simple, pictorial form. It is difficult to properly integrate constructibility information into the PDP *without* a formal, well-understood process in place. STAs must start to document their current PDP.

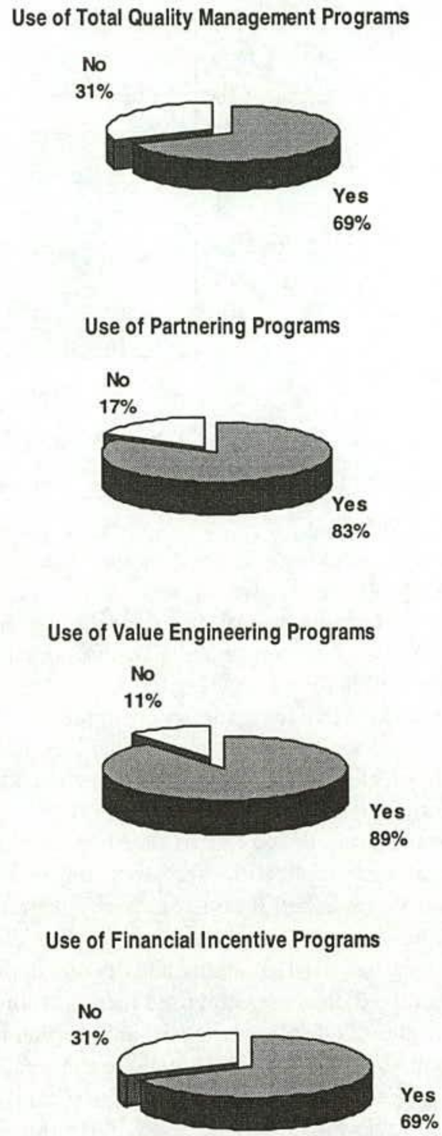

Figure 9. Use of special programs by STAs.

Software, Hardware, and Computer Tools for Implementation

All agencies responding to the survey were heavily involved in computerization and its application to project work. Each responding agency had, for example, an information systems/computer/technology manager. Figure 10 provides the average estimate of the percentage of project activities performed using computers in each major project development phase. Eighty-six percent of design activities was performed using computers. Figure 11 shows the frequency at which selected project activities are performed on mainframes, workstations, and personal computers. The activities evaluated in the survey included project planning, project scheduling, contract preparation, specification development, design drafting, engineering calculations and analysis, traffic control planning, and cost estimation. Personal computers appeared to be the dominant platform for many of these computing applications.

In general, most STAs used the mainframe to perform activities, such as project scheduling and cost estimation. Personal computers were frequently used for specification development, preparing contract documents, and traffic control planning. Workstations were used to perform design drafting and engineering calculations and analysis. Finally, most STAs that responded had networking capabilities, linking districts or divisions (86 percent). The most frequently

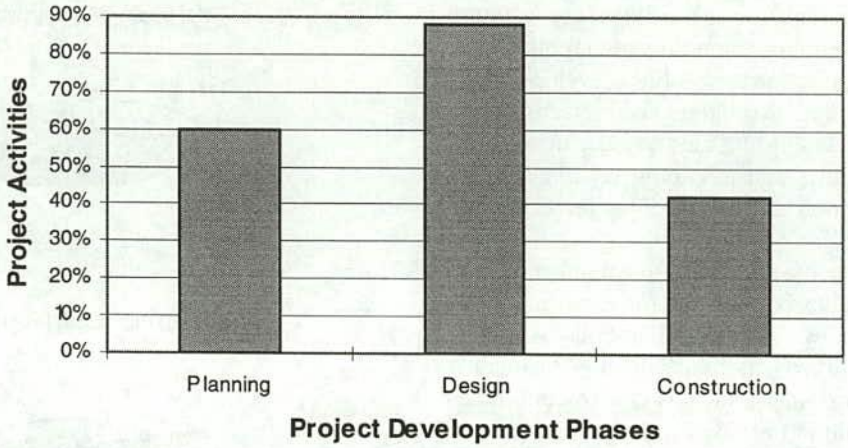

Figure 10. Average percentage of project activities performed using computers.

listed networks included Internet, Ethernet, Local Area Networks, and Wide Area Networks.

Indicators of computerization capability within STAs from the questionnaire suggested that the potential to use computer-based analytical review tools for constructibility was high, provided that these tools were applicable. This was encouraging, because there exists a capability to automate the CRP in selected areas, such as through a constructibility lessons-learned database support system.

Several questions in the Part II questionnaire addressed computer software applications for supporting constructibility reviews. When asked if constructibility lessons learned were documented by STAs, only four agencies (20 percent) stated that they had tried to capture and document them. Two had computerized databases and used them as training vehicles for designers. The other two used an informal filing system to capture lessons learned. Only three states (12 percent) stated they used computer aided design (CAD) for constructibility reviews. One state used CAD during design development for improving constructibility of the design. Only one state agency stated that they use GIS when addressing constructibility issues. This application was related to receiving utility location information from a utility company's GIS. However, 31 STAs indicated the use of computer simulations for developing project traffic control plans. Traffic control had been cited by many agencies as a critical issue, and its resolution by computer simulation certainly could enhance an overall project CRP if simulation analysis incorporates constructibility input.

Constructibility lessons-learned databases, CAD, and GIS were potential tools that could support the CRP. Their applicability to this process was examined when developing the CRP. Capturing, documenting, and retrieving lessons learned was an extremely critical aspect of constructibility. The importance of this attribute of a formal constructibility process has been documented in previous research (*3,5,10*).

INTERVIEWS

Five state transportation agencies were interviewed: Arizona (ADOT), Florida (FDOT), New Mexico, Virginia (VDOT), and Caltrans, District 12 (California). In addition,

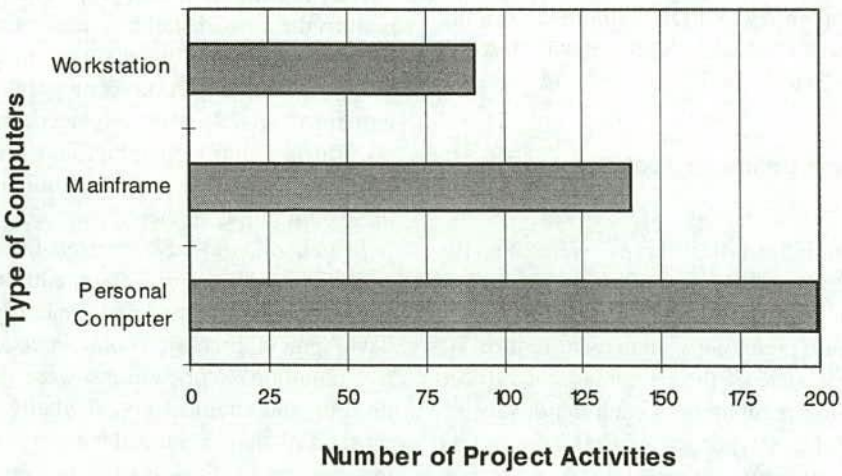

Figure 11. Frequency at which selected project activities are performed on mainframes, workstations, or PCs.

one design firm, Greiner Engineering, was interviewed in California. The main purpose of the interviews was to obtain specific input on both the PDP for transportation projects and constructibility as applied during the process. This information supported the development of the CRP framework.

Topic areas, with discussion points, were developed for the interviews and sent to each participant before the visit (see Appendix A). The five STAs were chosen because they were actively pursuing a formal constructibility program. The design firm was also developing a formal program and frequently performed work for District 12 of Caltrans. Each interview had at least two persons representing both design and construction perspectives. Some general observations from these interviews are discussed next.

The STAs interviewed had documented procedures and guidelines that described their constructibility reviews. These reviews were tied to established review points during design. Supporting checklists were available to guide the review process. The main constructibility effort appeared to take place during design. Constructibility was addressed less frequently, if at all, during project planning when scoping and schematic plans were developed.

FDOT, ADOT and Caltrans used a team approach to constructibility, headed by a project manager. The team included in-house construction expertise. This type of team approach provided continuity throughout the project. While most constructibility input occurred at review points, the team also provided informal analysis as the need arose.

ADOT had hired a full-time constructibility engineer. His charter was to provide a resource for constructibility input for both designers and contractors throughout the project development process. He was also responsible for implementing a constructibility process designed by him for ADOT (*9*). ADOT planned on expanding their process to be more continuous and proactive during all project development phases. Adding this position suggested a high-level commitment to constructibility implementation within ADOT.

ADOT, Caltrans, and FDOT all sought outside sources to supplement their constructibility efforts. This included retired contractors, suppliers, and contractor associations. FDOT sponsored an annual training school for 15 FDOT and 15 contractor personnel. Various FDOT training programs incorporated constructibility concepts. FDOT had participated in a study by the University of Florida that proposed the incorporation in the initial design phase of a constructibility review, as well as a post-construction review. These states were not actively tracking lessons learned related specifically to constructibility, but post-construction reviews were employed on selected projects to enhance feedback to designers on construction-related problem areas. VDOT and FDOT were very active in this later area; ADOT was beginning to develop a database directly related to constructibility.

A series of interviews was held with various personnel involved with the New Mexico State Highway and Transportation Department. Project development phases in New Mexico were documented by a formal procedure (Activity Responsibility and Description Manual), but this procedure was either unknown (Part II questionnaire indicated no formal procedure) or was not followed, except on an informal basis. Constructibility was cited as an important issue during National Quality Initiative Conferences, but as far as any direct follow-up from that conference, none was known. Issues of concern with regard to constructibility were as follows: the shortage of resources (people and time) to adequately review designs; the fact that designs were typically conducted at a centralized point (Santa Fe), but that the knowledge was decentralized at the district/contractor level; the need for a good scoping report; and the fact that traffic control scoping/construction phasing was performed too late in the design process, creating problems with utility relocation and right-of-way issues.

Greiner Engineering's level of constructibility input during design depended on how much the client was willing to invest in their constructibility program. If a less formal effort was preferred, then the project manager had major responsibility for implementation. Greiner had a formal process that included 11 steps. Use of this process involved a constructibility task force and formal approval of the client.

OBSERVATIONS ABOUT CURRENT PRACTICE

Current constructibility processes were extremely review-driven, focusing on predetermined milestones points for reviews. Most were informal. There was heavy reliance on expertise of design personnel and in-house personnel with construction experience to provide input during these reviews. There was minimal use of consultants or project/construction managers for providing construction knowledge and experience. When STAs contracted design, they relied on the design firm to produce complete plans and specifications. Reviews were used to ensure constructibility of the plans and specifications. Lessons learned regarding the constructibility of projects were not captured in documented form.

CHAPTER 3

CRITICAL ISSUES IN IMPLEMENTATION

INTRODUCTION

This chapter evaluates critical issues involved in implementing constructibility. The Part I questionnaire was used to identify these critical issues. Findings from this questionnaire reflect the perspective of STAs, design firms, and construction firms. Respondents were asked to list three issues pertinent to implementing constructibility. All issues were first analyzed and then categorized by similar problem areas. The number of times a general issue was cited was then recorded in terms of both frequency and percent of all responses. These data were summarized for each of the three types of organizations. Results of this analysis are shown in Table 2.

The critical issues reported in response to the Part I questionnaire were, without exception, issues that would impede or act as barriers to the constructibility process in the view of STAs and design and construction firms. Issues were stated with particular reference to their impact on the various phases or functions of project development.

While responses to the Part I questionnaire were excellent, additional agency-level issues were identified through the Part II questionnaire and interviews, the review of literature from various departments of transportation, as well as by observations of the Research Advisory Team. These particular issues are outlined in the last section of this chapter.

The discussions that follow focus on those critical issues that, as discussed above, impede the CRP. They encompass approximately 70 percent of the responses. A short discussion of each issue is provided, based on the responses and comments from the Research Advisory Team, and researchers' assessment.

STATE TRANSPORTATION AGENCIES' OBSERVATIONS

Lack of Feedback to Designers

The contracting environment STAs operate in make it a challenge for designers to obtain construction feedback for future project planning and design. By the time that the contractor enters the project, the design is usually 100 percent complete. This clear separation between the design and construction phases makes it difficult to apply constructibility. One mechanism to obtain construction feedback for use during planning and design is by developing a lessons-learned database. However, without a formal CRP, use of such a database is limited.

Need to Improve Plans and Specifications

Ease and simplification of the construction process is the main goal of implementing a CRP. Poor plans and specifications can cause major delays, claims, and rework. Many agencies consider the need to improve plans and specifications a major issue in achieving a constructible project. The effective communication of engineering information is crucial to achieving efficient construction, resulting in time and cost savings. In the transportation industry, the effectiveness of the plans and specifications takes even greater importance because of the separation of the design and construction phases. Improved plans and specifications remains the best approach to conveying the design intent to contractors. Constructibility reviews would help communicate the design intent, thus enhancing a project's constructibility.

Inadequate Time to Review

The time required to implement constructibility reviews is critical to many agencies. Their main concern seems to be the lack of time to apply a detailed analysis of designs from a construction perspective. Maintaining the status quo is considered the quickest way to meet the design schedule. Changing the process may be considered a potential source of delay in design operations. Both the Florida and Virginia DOTs stated that increasing pressures to meet schedules has actually influenced their formalization of constructibility reviews in an attempt to make them more efficient.

Lack of Practical Construction Experience by Design Personnel

The separation of design and construction phases in the design-bid-build contracting environment makes it difficult for designers to gain construction experience. Once the design is complete, most designers leave the project. The lack of any formal requirement to maintain a lessons-learned database will hinder the process even further. Experienced designers have few mechanisms for passing their knowledge to newly hired personnel.

Traffic Control

The success of a project often depends on an adequate level of traffic control planning. Poor traffic control management can result in major delays, safety hazards, and costs. Construction input can be valuable to the development of an effective traffic control plan. Lessons-learned databases could also help in this area. Studies should be performed on site characteristics and traffic patterns that will result in maximum savings in time and overall cost of the project. This analysis should begin early during the planning phase and include construction input.

Cost

The cost of implementing a formal constructibility process is a concern for many agencies. Investing money up front has always been a deterrent to implementation of constructibility in the construction industry (*4*). It is crucial that agencies understand that benefits returned will more than offset costs to implement and apply a formal CRP. Benefit/cost data confirms this and reflects a $25 project cost savings for every dollar spent on constructibility reviews.

TABLE 2 **Summary of critical issues Phase I survey**

	State Agencies' Issues	Frequency	Percentage
A	Lack of feedback to designers	17	14
B	Need to improve plans and specifications	14	12
C	Inadequate time to review	12	10
D	Lack of practical construction experience by design personnel	11	9
E	Traffic control	10	8
F	Cost	8	7
G	Geotechnical issues	7	6
H	Manpower	7	6
I	Environmental factors	6	5
J	Better/Earlier input from district construction personnel	6	5
K	Need to include construction contractor in the review process	5	4
L	Maintenance & operations	5	4
M	Communication	4	3
N	Creating an accessible database	3	3
O	Safety	3	3
P	Balancing with other social, economical factors	1	1
	TOTAL	**119**	**100**
	Design Firms' Issues	**Frequency**	**Percentage**
A	Inadequate coordination of designs, plans, and specifications	35	17
B	Lack of experience and knowledge	31	15

TABLE 2 Summary of critical issues Phase I survey (*continued*)

C	Poor communications and feedback	30	14
D	Inadequate time and funds for constructibility	19	9
E	Early review of designs	16	8
F	Uncoordinated timing, phasing, and scheduling	14	7
G	Lack of contractor input	13	6
H	Traffic control	12	6
I	Commitment to quality work	12	6
J	Availability of materials and skills	10	5
K	Environmental concerns	7	3
L	Interaction with DOT	7	3
M	Site access	3	1
N	Use of standard methods	3	1
	TOTAL	**212**	**101**
	Construction Firms Issues	**Frequency**	**Percentage**
A	Unclear designs, plans, and specifications	21	17
B	Poor scheduling and phasing of construction	17	14
C	Lack of communications and feedback	13	10
D	Lack of experience and knowledge	12	10
E	Design review	12	10
F	Construction operations and safety	11	9
G	Interaction with DOT	8	6
H	Availability of materials and equipment	7	6
I	Traffic control	7	6
J	Insufficient use of standard designs and methods	5	4
K	Environmental concerns	4	3
L	Site access	3	2
M	Need to remain competitive	3	2
N	Commitment and time for constructibility	2	2
	TOTAL	**125**	**100**

Staffing

Assigning personnel exclusively for the purpose of constructibility could result in increased cost to the agency. This is a difficult issue especially with many agencies downsizing their operations. Hence, the process has to be flexible enough so that implementation can fit into the actual structure of the agency without adding substantial new staffing requirements.

DESIGN FIRMS' OBSERVATIONS

Inadequate Coordination of Designs, Plans, and Specifications

This issue addresses the lack of coordination between designers and constructors that results in poor coordination and interaction with construction. It has been stated by respondents in terms of (a) not enough design detail for construction; (b) inefficient and inflexible designs; (c) designs not coordinated with utilities within the scope of the project; and (d) a lack of clarity in design criteria that must be met by the project. This issue becomes even more critical in its relation to other significant issues that impede constructibility: poor communication and feedback; inadequate application of construction experience; and lack of contractor input to the design process.

Lack of Experience and Knowledge

It was evident from responses within the design community that a major issue with respect to facilitating the CRP is the lack of construction experience and knowledge among designers. This issue is resolved within most firms by assigning design review responsibilities to senior design personnel. However, it is apparent that this effort does not effectively bridge the gap between designers and constructors so that efficient constructibility analysis results.

Poor Communication and Feedback

Unfortunately, this issue is one that is common to organizations with inefficient internal operations and it is especially critical with respect to constructibility. Communication about project designs, plans, and specifications must be clearly understood by everyone involved in, as well as across, the interfaces of the planning-preparation-review processes. Communication must be similarly understood by the contractor who is expected to implement designs. Feedback is essential to the "learning process" and, unless encouraged and acted upon, offers little to support the final outcome of a project. As indicated, this may be accomplished by the establishment of a project lessons-learned data file.

Inadequate Time and Funds for Constructibility

This response is indicative of what seems to be the traditional method of performing work with regard to the planning-design-construction process. Constructibility has not been embraced by many organizations to date, and time and funding for this process simply have not been allocated for such an effort. As with programs such as VE, partnering, and TQM, constructibility must have the support of an organization's leadership and management personnel so that time and funds may be allocated and benefits realized from these programs.

Early Review of Designs

The review of designs early in the project process was deemed necessary by numerous respondents as essential to the completion of correct and detailed designs. Because this issue has been raised, many design organizations must believe that early review is an area in which there is a shortfall of effort.

Uncoordinated Timing, Phasing, and Scheduling

This issue has been mentioned by respondents with respect to design activities that take place in an uncoordinated manner, as well as construction activities that are not well timed, scheduled, and coordinated. It is noteworthy, too, that this issue is critical to effective project management across the design/construction interface and is related to some of those issues indicated above, such as poor communication and feedback. It is fundamental that such issues must be managed and overcome so that constructibility can be realized throughout the overall project process.

CONSTRUCTION FIRMS' OBSERVATIONS

The five most critical construction firm issues are listed below. They are each listed among the design firm issues that have already been discussed, and their potential impact on constructibility is similar to that described for design firms.

- Unclear designs, plans, and specifications
- Poor scheduling and phasing of construction
- Lack of communication and feedback
- Design review
- Lack of experience and knowledge

CRITICAL ISSUES FROM OTHER SOURCES

Several more general issues concerning implementation of constructibility by STAs surfaced as the preliminary CRP framework was developed. The following issues were cited as extremely important to successful implementation by the Research Advisory Team and the literature on constructibility.

1. Implementation of a CRP has to have a clear mandate from senior agency policy makers. This mandate may be put forth in an organization by policy memoranda or other instructions that are well understood by all personnel involved in the CRP. Anything less than such instructions, once a decision is made that the organization will implement the process, would be unsatisfactory. This is supported by research in the private sector regarding constructibility (*5*).
2. The CRP must have a constructibility champion who serves full-time in this capacity. In addition to such a program manager, there must be clear support shown by the head of the organization. This is also supported by research as a critical factor for successful organization-level implementation (*5*).
3. Funds and other resources must be provided to support such a program, including specific requirements and funding for outside consultant support, contractor associations, and design firms.
4. Formal databases of constructibility lessons learned and identification of best practices associated with constructibility approaches must be developed. Most private companies that are implementing constructibility are doing so by actively developing lessons-learned databases. For STAs, this will require commitment of agency personnel and other resources during planning, design, and construction to capture and retrieve lessons learned. There must also be a screening process to select the most critical lessons learned. Simplicity is important, and controlling the growth of the database is a concern. Thus, the use of constructibility lessons learned does not come without potential problems that need to be addressed.
5. A shift from review-driven constructibility practices to more continuous application of constructibility concepts and ideas during planning and design must be considered if a CRP is to become fully developed. The former way of approaching project development simply reinforces traditional practices and does nothing to improve upon constructibility processes in general.

CHAPTER **4**

INTERPRETATION OF CURRENT PRACTICE AND CRITICAL ISSUES

INTRODUCTION

This chapter interprets the findings relevant to current practice and critical issues. This information served as a key driver for using a process modeling technology to develop the preliminary CRP. Also, guidance in tool development was provided through the interpretation of current practice and critical issues.

CURRENT PRACTICE

This section interprets the findings from the Part I and Part II questionnaires and interviews, and proposes tools and analysis methodologies that address current practice. Using a Pareto analysis of Part I and Part II questionnaire findings with regard to current constructibility practices, Table 3 summarizes key characteristics of state agencies that need to be considered when developing a CRP framework. Items 1 through 3 are taken from the Part I questionnaire, items 4 through 11 are taken from Section 1 of the Part II questionnaire, and items 12 through 17 are a summary of Section 2 of the Part II questionnaire (see Appendix A to review specific questions).

Twelve of the 17 key characteristics covered in the current practice analysis, as shown in Table 3, suggest a need for tools and a methodology for process modeling. This conclusion considers the impact that change will have on agency project execution approaches and how current constructibility practices may be altered by applying a new CRP. The other five key characteristics indicate a need for innovative alternatives in tools, such as partnering and alternate contracting strategies.

CRITICAL ISSUES

Critical issues from the Part I questionnaire are condensed and grouped into three basic categories, as shown in Table 4. These categories are: (1) project execution process; (2) project planning and technical design documents; and (3) project resources. They were derived by grouping critical issues from Table 2 into common areas and then ranking them based on total frequency of response. The alpha characters in Table 4 were used as the issue identification letter from Table 2, and the numbers in the adjacent columns are the response frequencies, also extracted from Table 2 for each issue. Table 5 summarizes, in words, critical issues by issue category perspective to assist in understanding the interpretations discussed next.

The magnitude of the frequencies as noted in Table 4 is not as important as their relative comparisons among one another. Agencies seem to consider the three categories equally important, probably because they are involved in the project throughout its life cycle and see a broader perspective. Design firms are most concerned with the general project execution process as it relates to coordination among the different participants in the project. They are less concerned with resources and with the quality of design, maybe because they are not eager to criticize the quality of their own work. Moreover, design firms may view quality as perhaps influenced more by the project execution process. Construction firms are eager to stress the unclear quality of designs, plans, and specifications, more so than project execution and availability of resources. Contractors have to make the design work and are often critical of designers, especially when they are unaware of decisions and constraints related to the project. The following sections describe these three categories in detail and propose necessary tools and analysis methods to address them.

Project Execution Process

When critical issues were first solicited in the Part I questionnaire, the request was for issues relevant to the implementation of constructibility in general. This questionnaire did not request issues specifically related to the project level. It is interesting to note that the highest total frequency of occurrence was at the project execution process level. Issues in this group included feedback; time for reviews; early input; construction input; maintenance/operations input; communication; coordination; interaction; and the competitive bidding process. This group indicated the potential need to use a process modeling technique and tool that defined and addressed the interaction of constructibility steps at the

TABLE 3 Summary of state-of-the-art practice

State Agency Characteristics	Tool Area/Analysis Methodology Needed
Part I Survey	
1. Medium to high in-house use of resources for planning and design	process modeling
2. Late constructibility input during project execution process	process modeling
3. Mostly informal constructibility procedures and practices	process modeling
Part II Survey - Section I	
4. Minimal use of constructibility related contract clauses	contracting tool
5. Agencies utilize TQM, partnering, VE, financial incentives at agency level	process modeling
6. Programs identified in item #5 are not used extensively at project level	partnering/contracting/value engineering and incentive tools
7. Majority of state agencies have not graphically documented conventional project development process	process modeling
8. Mostly centralized management of project planning and design	process modeling
9. Design-bid-build is normal approach to project delivery	contracting tool
10. Minimal use of outside consultants for constructibility reviews	contracting/constructibility resource tools
11. Majority of agencies use matrix or functional project organization structures	process modeling and team building tool
Part II Survey - Section II	
12. All agencies have information systems/automation management type position	process modeling
13. Average percent of activities performed using computer : 60% planning, 86% design, 42% construction	process modeling
14. Agencies have some networking capacity	process modeling
15. Minimal use of lessons learned databases, CAD, GIS, simulation, benefit/cost to support constructibility analysis	computer tools
16. Personal computers used most frequently (for planning, word processing - specs/contracts); mainframes have next highest level of use (for scheduling, estimating); workstations used the least of these three (for drafting, engineering analysis)	process modeling
17. Large mix of different types of software being used for project execution activities	process modeling

detailed project level and document the interrelationships among these steps. The process modeling technique must also capture inputs from the PDP and display where these inputs are used when applying constructibility, especially as related to planning, design, and construction.

Project Planning and Technical Design Documents

Once again, issues were identified at the project level in the Part I questionnaire, even though they were not directly solicited for projects. The second highest total frequency of occurrence was also identified at the project level. Issues here dealt with the quality of detailed project planning and design documents and the need for their improvement. Specific planning and design issues focused on plans/specifications, traffic phasing/staging, general phasing/scheduling, geotechnical, environmental, safety, social/economic factors, accessibility, and standardization of design/methods. This indicated the need for a process that would lead to improvement in the quality of, at the very least, the top five mentioned project activities (plans/specifications, traffic phasing and staging, general phasing and scheduling, environmental, and safety). Again, a modeling technique that identified the steps required to perform timely constructibility analysis and reviews of documents produced

TABLE 4 Summary of critical issues (from Table 2) and needed tools/methodologies

Agency Issues		Design Firm Issues		Construction Firm Issues		Total Frequency	Needed Tool/ Methodology
Designation (Table 2)	Frequency	Designation (Table 2)	Frequency	Designation (Table 2)	Frequency		
A	17	A	35	C	13		Process Modeling Technique
J	6	C	30	E	12		
K	5	E	16	G	8		
L	5	G	13	M	3		
M	4	L	7				
Total	37	Total	101	Total	36	174	
B	14	F	14	A	21		Detailed Modeling of Process to Review Technical Documents for Constructibility
E	10	H	12	B	17		
G	7	I	12	F	11		
I	6	K	7	I	7		
O	3	M	3	J	5		
P	1	N	3	K	4		
				L	3		
Total	41	Total	51	Total	68	160	

TABLE 4 Summary of critical issues (from Table 2) and needed tools/methodologies (*continued*)

Agency Issues		Design Firm Issues		Construction Firm Issues		Total Frequency	Needed Tool/ Methodology
C D F H N	12 11 8 7 3	B D J	31 19 10	D H N	12 7 2		Tools to identify timing of project resources and need for automated systems
Total	41	Total	60	Total	21	122	

TABLE 5 Critical constructibility issues

	Project Execution Process	Project Planning & Technical Design Documents	Project Resources
Owner	Lack of • Feedback to designers • Timely input from district construction people • Input from construction contractor in the review process • Maintenance and operations inputs • Communications	Lack of • Need to improve plans and specifications • Traffic control • Consideration of geotechnical issues • Consideration of environmental factors • Safety • Balancing with other social, economic factors	Lack of • Adequate time to review • Practical construction experience of design personnel • Cost considerations • Personnel • An accessible database
Designer	Lack of • Adequate coordination of designs, plans & specifications	Lack of • Coordinated timing, phasing and scheduling • Traffic control	Lack of • Experience and knowledge

TABLE 5 Critical constructibility issues (*continued*)

	Project Execution Process	Project Planning & Technical Design Documents	Project Resources
	• Quality communications and feedback • Early review of designs • Contractor input • Interaction with DOT	• Commitment to quality work • Environmental concerns • Site access • Use of standard methods	• Adequate time and funds for constructibility • Availability of materials and skills
Contractor	Lack of • Communications and feedback • Design review • Interaction with DOT And • Need to remain competitive	Lack of • Clear designs, plans & specifications • Quality scheduling and phasing of construction • Construction operations and safety considerations • Traffic control • Sufficient use of standard designs and methods • Environmental concerns • Site access	Lack of • Experience and knowledge • Availability of materials and equipment • Time and commitment for constructibility

by the previously mentioned project activities was deemed necessary.

Project Resources

Consistent with previous results, the shortage of resources was again identified at the project level (see third category in Table 4). Specific resources that lack adequate levels were time, experience, money, people, accessible databases, materials, skills, and equipment. The process modeling technique must specify where, when, and what functions require these resources. It must also show where tools are applied to aid in facilitating function performance.

SUMMARY INTERPRETATION

Table 3 indicated the need primarily for a process modeling technique that documents how current approaches are altered by a reengineered CRP. This technique should formally document the constructibility process, indicating an increased level of input of construction knowledge and experience during early project phases. Moreover, the technique should show how the CRP is integrated with a conventional PDP for organizations that have centralized planning and design based primarily on in-house design. It should also consider how matrix and functional project-type organizations can lend themselves toward increased cross-functional constructibility reviews. The technique should have the capability of demonstrating how existing resources (i.e., information systems/automation departments, standardized hardware and software platforms, and networking capabilities) are linked to constructibility functions. Table 3 documents other innovative alternative tool types that would include partnering and contracting clauses, methods, and procedures and constructibility computer tools, such as databases, CAD, GIS, simulation, and benefit/cost analysis.

The final column of Table 4 indicates the primary need for tools and analysis methodologies that have the capability of modeling attributes of a CRP that make project execution more efficient, highlighting interaction among steps in the process. These methods also should have the capability of highlighting the planning and design activities in the context of the CRP perspective. Finally, tools must identify the level and timing of resources needed for quality constructibility reviews, considering the automation of some of these processes in order to optimize resources.

CHAPTER 5

PRELIMINARY CONSTRUCTIBILITY REVIEW PROCESS MODEL

INTRODUCTION

A basic premise behind modeling the CRP was to link different project development phases to constructibility functions that occur during each phase. Three major project development phases were defined in this research: (1) planning, (2) design, and (3) construction. Consequently, the framework for the model has three levels of detail. Information collected through literature reviews and identification and analysis of critical issues guided the development of the framework. This framework portrays a generic set of constructibility functions for each project phase. Based on the framework, a model was then developed that defined when and how constructibility input should be applied during each phase.

The model was based on a flexible approach that can be adapted to different project characteristics and agency organizational environments. The proposed CRP was also based on similar constructibility steps as shown in the WisDOT work process; (*10*) but it was enlarged to include more specific functions that are linked to one of three project development phases. Moreover, key information, resources, and guidelines have been identified for each function. The goal of identifying and describing key functions, associated information flows, and resource requirements for constructibility reviews for transportation agencies was largely met through the preliminary CRP model.

MODELING APPROACH

To formulate the CRP, a modeling technique was required that permitted the design and layout of a process. This technique must also capture functions (activities or steps) and key information supporting the performance of these functions. Finally, modeling relationships between different constructibility functions, as well as between project development phases, was a key requirement of the technique.

Based on these criteria, IDEF0 function modeling was selected to develop and portray the CRP. This technique formalizes a process by identifying the primary functions of the process and representing them in a structured procedural form. IDEF0 uses Cell Modeling Graphic Representation as shown in Figure 12 (*27*).

Figure 12 shows a function (the box) and the interfaces to or from the function as arrows entering or leaving the box. The **input**, information needed to perform the function, is transformed by the function to provide **output**, information produced by the function. **Controls**, arrows coming into the top of function box, are information that govern the accomplishment of the function. **Mechanisms**, arrows entering the bottom of function box, are people or tools that help perform the function. Functions are described by short verb phrases. Inputs, outputs, controls, and mechanisms are described by noun phrases. As an example, *Evaluate Draft Plans and Specifications for Constructibility* is a function. Input for this function might be *draft plans and specifications.* An output of performing this function would be *constructibility improvements.* A mechanism for function performance is a *constructibility team.* Finally, a control could be the *project constructibility procedures for design* that determines the frequency at which this function will be performed. The process is represented at the first level by one general box called the **context diagram**. The context diagram represents the whole system as a simple unit-box with arrow interfaces to functions outside the system. Since the single box represents the system as a whole, the descriptive name written in the box is general. This general box is then decomposed into subprocesses or functions with further details and more interface arrows between functions as illustrated in Figure 13. Each successive level of the diagram becomes increasingly more specific.

The model is hierarchical in nature, that is, lower-level diagrams are decompositions of the upper-level diagrams immediately preceding them (see Figure 13a). In the case of the CRP model, the first level, or context diagram, is a broad application of constructibility to a transportation project. The next level is more specific, and the functions at this second level include applying constructibility to the planning, design, and construction phases of the project development process (PDP). The third level is a decomposition of planning, design, and construction into yet more specific subphases that occur during each of these major project development phases. Finally, the fourth level represents the actual constructibility functions performed during each project development phase.

PRELIMINARY CRP MODEL

The preliminary CRP model integrates constructibility functions with the PDP. This section describes the develop-

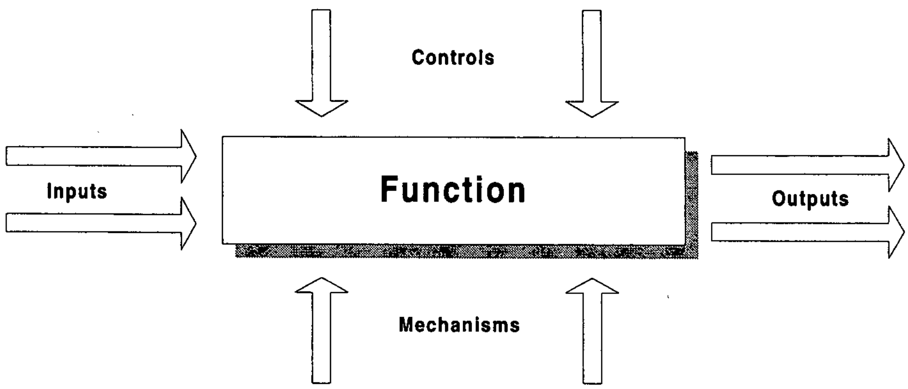

Figure 12. Cell modeling technique.

ment process of the model and examines its key features using the IDEF0 technique.

Purpose-Context-Viewpoint

A model is a representation and, in many cases, a simplification of a system (*27*). It describes what a system is, what it accomplishes, and what variables work on the system. IDEF0 describes a system by defining the purpose, context, and viewpoint of the model. The purpose of the CRP model is to document an integrated process for applying constructibility reviews to the planning, design, and construction of transportation facilities. The context of the model is the project life-cycle phases, that is, planning, design, construction, operation, and maintenance of transportation projects. The viewpoint is that of a STA, and more precisely, the group(s) responsible for project development of transportation facilities with STAs.

The concept of linking constructibility functions to the project development process, referred to as total constructibility management (TCM), is achieved by connecting both processes, that is, Project Development and Constructibility Review, through key inputs and outputs. Figure 14 shows this

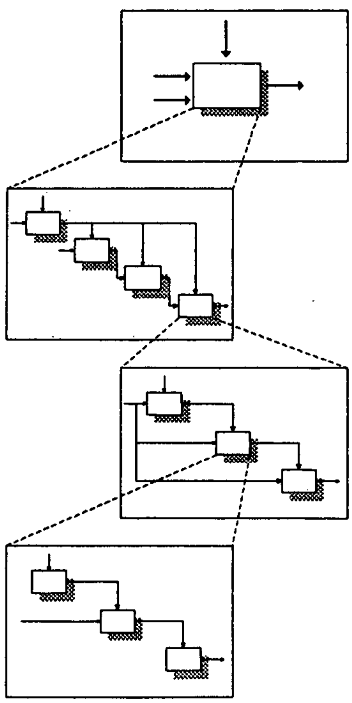

Figure 13a
IDEF0 Model Structure

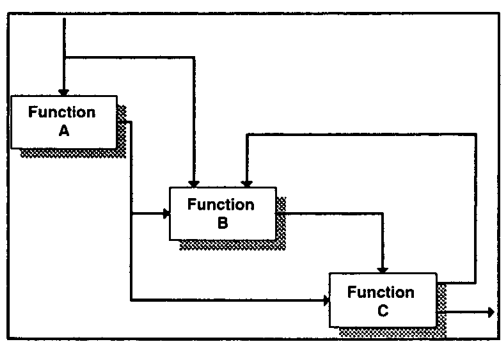

Figure 13b
Constraint Diagram

Figure 13. IDEF0 function modeling.

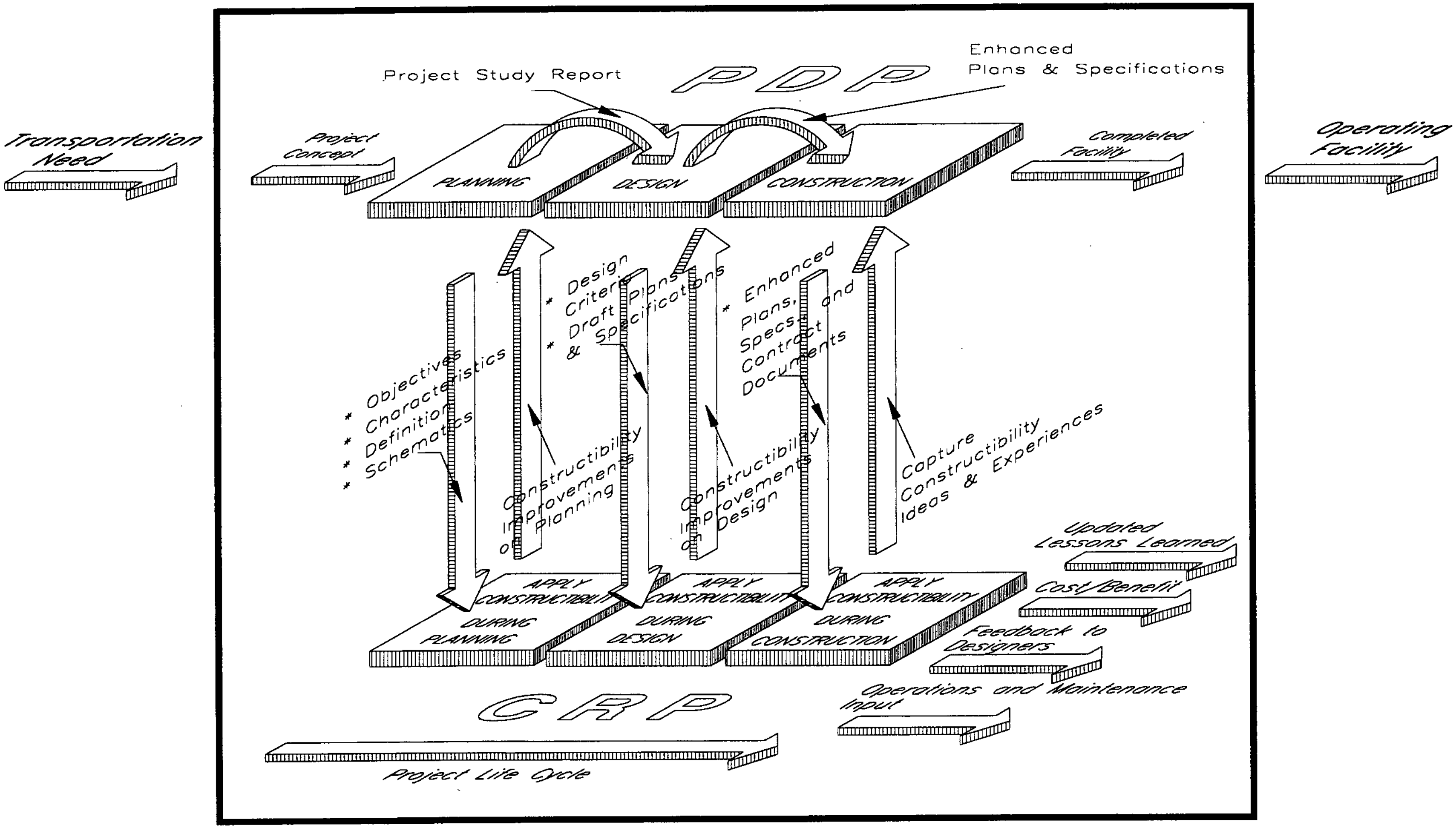

Figure 14.   Total constructibility management: integration of CRP with PDP.

TCM relationship in three dimensions. The boundary represents the context of the process system. The two parallel planes represent the PDP and the CRP. They both span through the entire project life cycle. The two processes transfer inputs and outputs to each other in a specific sequence. Key PDP inputs to the CRP reflect different project deliverables and information as illustrated in Figure 14. These inputs tie to the CRP at different points in the project life cycle. In turn, constructibility improvements are generated as outputs of the CRP and become inputs to the PDP. This exchange of information is iterative until each project phase is completed. Finally, as shown, updated lessons learned, benefit/costs, feedback from operations and maintenance personnel, and feedback to designers is vital input for use on future projects. This type of information flow leads to continuous improvement of the CRP.

Because the influence of construction input is greater during the early stages of the project than later when major decisions have already been made, more effort should be allocated to the planning and early phases of design regarding the constructibility functions. If constructibility improvements are continuously incorporated into design concepts and documents, the final reviews should require less time and produce better and more accurate plans and specifications. This will improve construction efficiency and result in fewer field problems during construction.

Preliminary CRP Framework

The final goal was to develop a process model that would be flexible enough to provide STAs with a working process that could be adapted to a specific project development approach. For this purpose, a general CRP framework was developed that comprised key activities occurring in the different phases of a transportation project. To maintain a process that is general and flexible, three levels have been developed, as shown in the process framework in Figure 15. The first two levels are a breakdown of the PDP phases, starting with a *first-level* breakdown into planning, design, and construction. The *second level* is a more detailed breakdown of each of these three major phases. Finally, the *third level* represents the proposed constructibility functions that would occur during each project development subphase. As an example, Applying Constructibility to Planning is decomposed into Apply Constructibility to Scoping and Apply Constructibility to Plan Development. Apply Constructibility to Scoping is decomposed into Establish Project and Constructibility Objectives, Determine Formality of Constructibility Program, and Identify and Evaluate Means to Obtain Constructibility.

The numbering system shown in the function box describes the hierarchical nature of the model (Figure 15). A0 is the context or summary diagram. A0 is decomposed into three functions: A1, A2, and A3. The decomposition continues until the desired level of detail is reached. For example, A1 is decomposed into A11 and A12. The final decomposition involves the breakdown of A11 in three constructibility functions A111, A112, and A113.

Summary Level Diagram

The summary level diagram (A0) is shown in Figure 16. At this level, the general function is described as **Apply Constructibility to Transportation Projects**. This function represents the overall project-level application of constructibility to the planning, design, and construction of transportation projects. The function box at this level is the context diagram. This function takes technical inputs from the PDP and evaluates them for constructibility. The results of these evaluations are outputs to the PDP in the form of improvements and other feedback. The function is performed by various personnel and implemented through constructibility tools and lessons learned. Function performance is influenced or guided by agency policies, and key project parameters such as project cost, schedule, and resources.

The *inputs* to the CRP are outputs from the different PDP phases as shown in Figure 14. They consist of objectives, characteristics, definitions, and schematics (planning phase); design criteria/basis and draft plans and specifications (design phase); and enhanced plans and specifications (construction phase). These inputs are linked to the CRP at different constructibility functions.

The *output* of applying CRP represents either constructibility input to the PDP at different points in the project life cycle or feedback from the CRP for use on future projects. Constructibility improvements on planning and design and constructibility experiences flow to the PDP. This flow of constructibility information occurs at interface points between planning, design, and construction phases and the CRP. On the other hand, formalized feedback to designers, lessons learned from maintenance and operation personnel, updated lessons learned, and benefit/costs are all *outputs* that feed the constructibility process for use on future projects.

Controls that influence the application of constructibility on transportation projects consist of project parameters and agency policies. Key controls cover agency constructibility policy, constructibility concepts, contract strategy, project complexity, and project constraints. These controls guide the level of formality, procedures used, and resources committed to implementation of constructibility.

Finally, *mechanisms* represent personnel and tools that are directly involved or used in performing constructibility functions (Figure 16). Key mechanisms include agency personnel, contractor personnel, engineers/designers, constructibility consultants/engineers, constructibility implementation tools, and lessons-learned sources.

Illustration of CRP at the Lowest Level of Detail

An illustration is provided of the preliminary CRP at the lowest level of decomposition using IDEF0 representation.

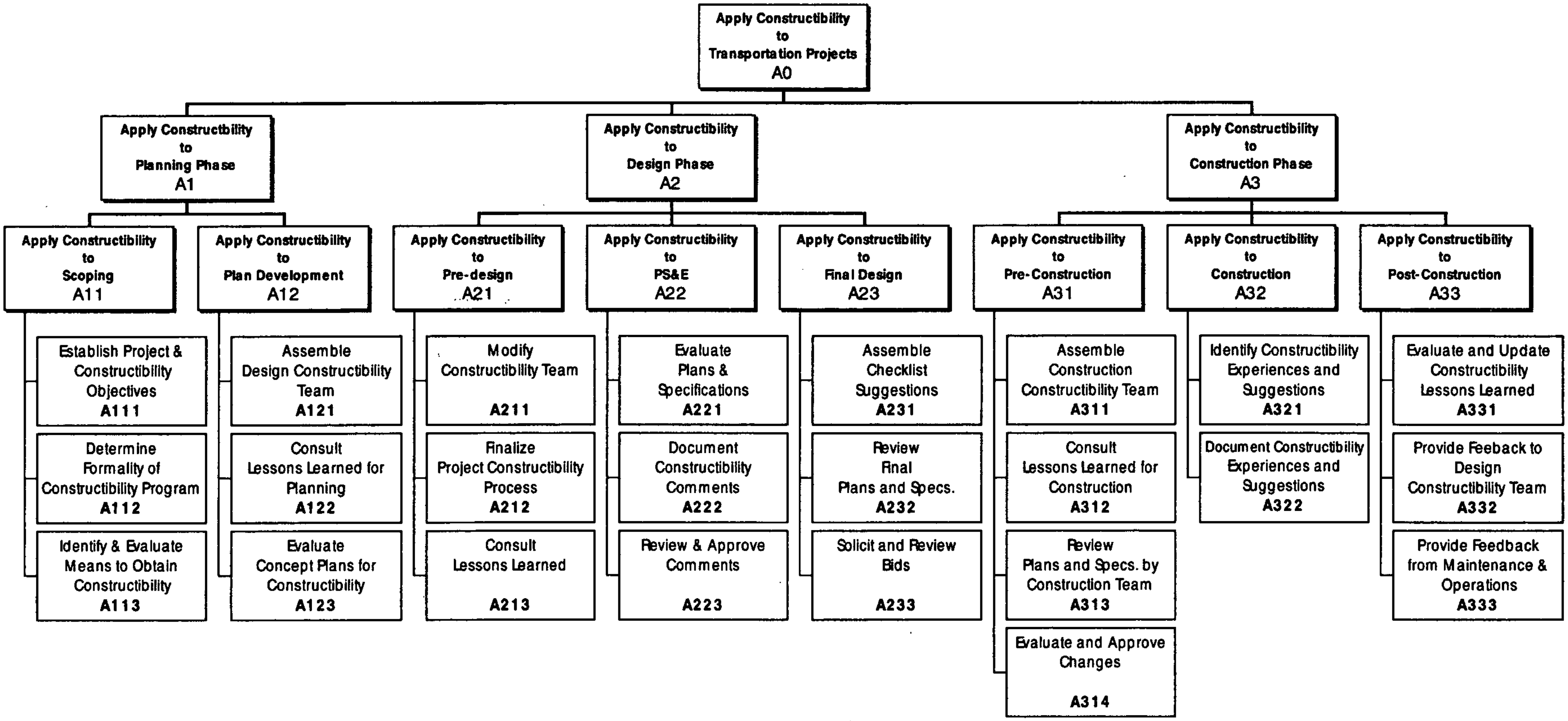

Figure 15. Preliminary CRP framework.

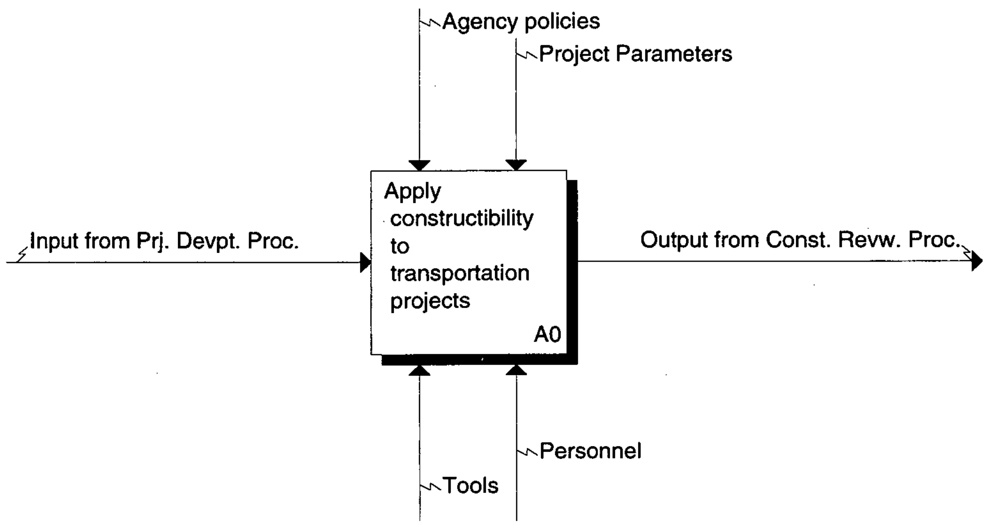

Figure 16. Summary-level diagram (A0).

This section provides the working details and interpretations of the process model. As an example, *Applying Constructibility to PS&E* (A22) is selected. It is decomposed into three constructibility functions as shown in Figure 17. Appendix B contains all IDEF0 models for the complete preliminary CRP model.

In general, constructibility is applied to the development of draft plans and specifications during the PS&E phase. Typically, design activities in this phase include right-of-way acquisition; detailed engineering and design of facilities such as pavement, bridges, utilities, and drainage; construction staging and traffic control plans; and final specification and

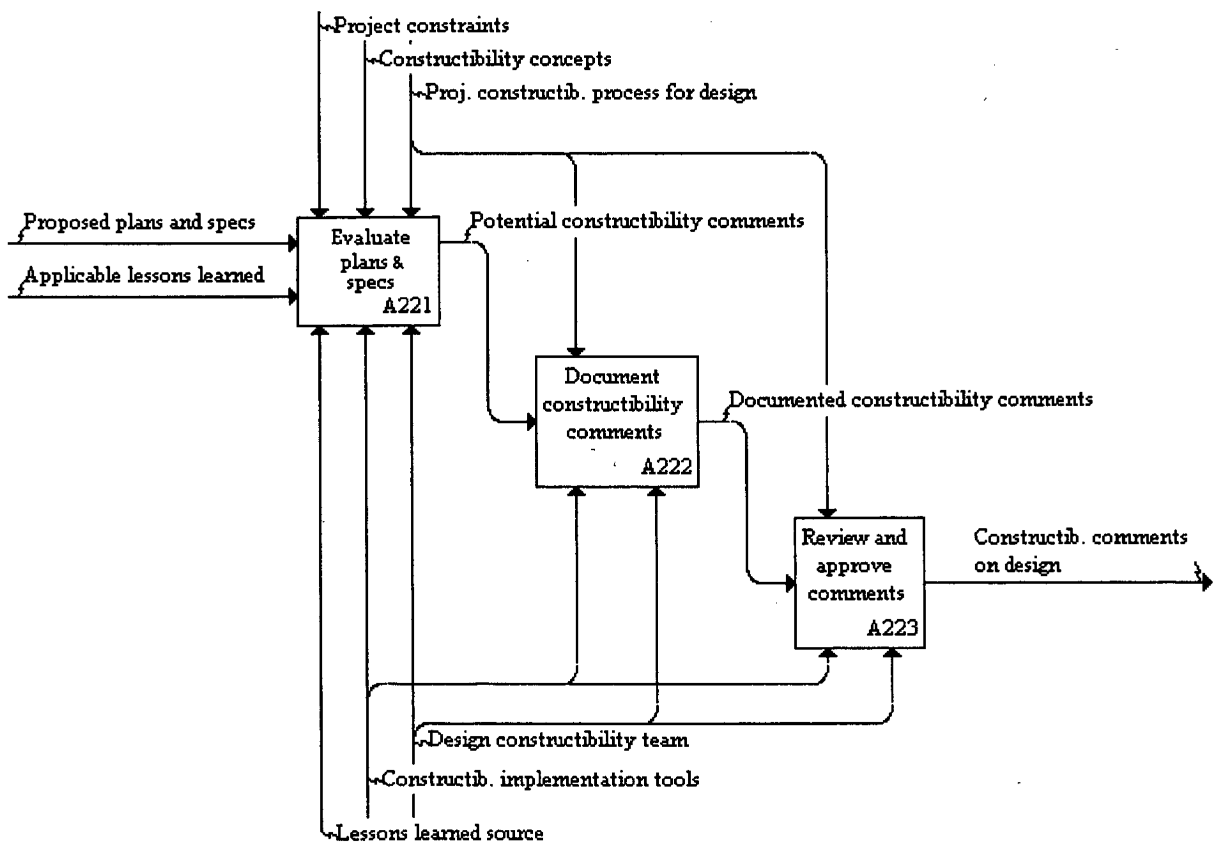

Figure 17. CRP at the lowest level of detail.

cost estimation. During this function, draft plans and specifications are evaluated and analyzed for constructibility; potential constructibility improvements are documented and then approved for incorporation into the design. These improvements are transmitted to designers in possibly an iterative fashion as the draft plans and specifications are being developed and reviewed.

Applying constructibility during the PS&E phase requires three functions, performed mostly in sequence as depicted in Figure 17. *Evaluation of Plans and Specifications* (A221) is initiated as draft plans and specifications (I2) are developed by engineers and designers. This input flows from the project development process. Another input, applicable lessons learned (I1), flows from an earlier constructibility function, *Consult Lessons Learned* (A213). These are potential lessons learned from past experiences that are believed to be applicable to the current project.

The manner in which *Evaluating Plans and Specifications* (A221) is performed will be influenced by the project constructibility process for design (Control C3). The formal project constructibility process is determined during preliminary design. This process is the output of the function, *Finalize Constructibility Process* (A212) as delineated on the framework (see Figure 14). For instance, if the process requires continuous reviews, then more effort and time will be required of the design constructibility team and most probably a full-time project constructibility consultant/engineer will be part of this team. Alternatively, if the process stipulates periodic reviews, say at 30, 60, and 90 percent of design completion, then the mix and effort required of the design constructibility team will change. Project constraints (C1) will influence timing of these reviews to the extent that funds and people resources may be limited.

The design constructibility team (M2) is responsible for performing this function. A common implementation tool (M1) used by the team is "constructibility review meetings." A "checklist" of common constructibility issues might be another tool to guide the analysis process. These tools, when combined with constructibility concepts, provide the vehicles to perform evaluations and reviews. However, in a more advanced constructibility review process, constructibility analysis might occur directly through the use of 3-D computer-aided design or the use of a multimedia tool such as that developed by McCullough and Patty for Indiana DOT (*11*). In these latter scenarios, the mix of the design constructibility team may change, as well as the manner in which this and the other two functions (A222 and A223) are performed.

When *Evaluating Plans and Specifications* (A221), ideas or suggestions for enhancing the design are considered as potential constructibility comments and, as such, become outputs of this function. Subsequently, they become inputs to the next function, *Document Constructibility Comments* (A222). At this stage, the constructibility team analyzes improvement ideas and documents the major potential improvements using a constructibility idea log. This document would identify the scope of the change, possible cost/schedule impacts, and other attributes.

Once the key constructibility comments are documented, this output becomes input to the final function of applying constructibility to PS&E, *Review and Approve Comments* (A223). Here, the design constructibility team must decide on whether or not each improvement warrants incorporation into the design. The project constructibility process for design should provide decision-making guidelines for selecting those approved improvements. Benefit-to-cost economic analysis might be one guiding criterion along with the impact the change might have on meeting the design schedule. Final and approved constructibility comments become improvements to design and are then transmitted to designers to be included in new revisions of the design documents.

The application of constructibility, as demonstrated in Figure 17, is often iterative to some degree for each project. Waiting until design is 90 percent complete for this type of review can result in major changes in the design that cost money and time. Thus, it is likely that the functions performed in Figure 17 will be repeated as engineering and design progress. In addition, as constructibility analysis and evaluation continue, the design constructibility team may seek other sources for lessons learned (M3), such as specialized expertise, if a particularly complex construction problem is encountered. One idea may result in extensive analysis and study before it is adopted as a constructibility improvement for design.

CHAPTER 6

FORMAL CONSTRUCTIBILITY REVIEW PROCESS MODEL

INTRODUCTION

As has already been pointed out, determination of critical issues regarding constructibility indicated the need for a formalized CRP. To fulfill this need, a preliminary CRP model was developed based on the literature review and survey results and the IDEF0 modeling technique. The CRP was revised further as it was reviewed by different STAs. Then extensive inputs from and reviews by the Research Advisory Team helped to develop the details of the complete model. Concurrently, a generic PDP framework was derived to adequately illustrate integration with the CRP. To evaluate CRP viability, the model was tested using actual projects. The model was found to be adequately adaptable to a variety of projects. A workbook was developed to convey the philosophy of the CRP and make CRP details easily understandable to users. Certain paradigm shifts have also been identified. These paradigm shifts are required at the agency level for sustained effectiveness of the CRP and at the project level to begin implementation.

DEVELOPMENT OF THE MODEL

The final CRP model was developed by means of the following two techniques:

1. **Concept Review**—use of process framework and components of the IDEF0 model and
2. **Research Advisory Committee Review**—detailed reviews of the framework, all components of the IDEF0 model, and a draft workbook of the CRP.

Concept Review

To formalize the CRP, the framework and model were reviewed by several STAs that agreed to participate including the Arizona Department of Transportation (ADOT), the New Mexico State Highway and Transportation Department (NMSH&TD), the Texas Department of Transportation (TxDOT), and the Washington State Department of Transportation (WSDOT).

Each of these review sessions consisted of three major activities:

- Discussion of the general concept of integrating constructibility with the PDP phases as depicted in Figure 14.
- Review of the constructibility functions shown in Figure 15, the preliminary CRP framework. IDEF0 models, such as Figure 16 and 17, were also used to facilitate the review process.
- Investigation of the applicability of the constructibility functions and their timing in terms of the PDP phases.

The CRP model was presented to and reviewed, *at first,* by the Chief of the Design Bureau for NMSH&TD, the Chief of the Preliminary Design Bureau for NMSH&TD, and the District Construction Engineer for Albuquerque (District 3). A *second review* was conducted by two Claims Engineers for TxDOT. A *third review* was conducted by the Design Program Manager, Value Engineer, and Constructibility Engineer, all with ADOT. Key results from these three review meetings were summarized as follows:

- Need to define constructibility and other critical terminology clearly at the beginning of the workbook (all three agencies).
- Add time milestones/activities to reflect approximately when in the PDP phases the various constructibility functions are performed (all three agencies).
- Consider increasing the number of constructibility functions in the early phases of project development (NMSH&TD).
- Number of constructibility functions satisfactorily describes the overall CRP, that is, there were no major functions missing (ADOT and TxDOT).
- Constructibility functions, as identified for each project development phase, were appropriately located within the PDP (all agencies).
- Ideas were offered on how to make the workbook user friendly (all agencies).

Finally, the CRP framework was presented to the WSDOT. WSDOT was represented by the Assistant District Administrator for Development, Design Management Engineer, and Project Development Engineer. Two academic delegates from the University of Washington, who were developing a constructibility implementation process for WSDOT, also participated.

The concept of beginning early in the project and using a team approach was consistent with the constructibility approach developed by the University of Washington. A major issue discussed was the need for continuous reviews versus periodic reviews driven by milestones. The new WSDOT Constructibility Review Project included three reviews at 30, 60 and 90 percent of design. This represented a significant departure from their traditional approach of one review late in design. Both positive and negative aspects of continuous reviews became obvious to participants of the meetings. Even with continuous reviews, it was recommended that milestone check-point reviews be maintained to ensure an overall project perspective, as constructibility comments are incorporated into design.

Research Advisory Committee Review

The CRP framework and IDEF0 model were thoroughly examined by members of the Research Advisory Team. The major focus of this first review was as follows:

- To analyze each function in the model to confirm that the function is required,
- To clarify the description of each function, and
- To confirm the proper location of every constructibility function within the overall CRP framework.

As a result of this detailed review, several function titles in the preliminary CRP (Figure 15) were changed, one new function was added to project definition (previously scoping), and each function description was revised and enhanced. In addition, several inputs and outputs were modified to better reflect the flow of information. It was also established that successful implementation of the CRP would require *paradigm shifts* as suggested later in this chapter. At the end of this review, the CRP framework was modified as shown in Figure 18.

The Research Advisory Team was also asked to provide additional input on each function to help prepare the workbook. The following input was requested:

- Help identify terminology and furnish definitions for functions at the second level of decomposition on the CRP framework (i.e., A11, A12, A21, etc.).
- Help identify detailed steps required to perform specific constructibility functions (i.e., A111, A112, A113, etc.) on at the third level of decomposition on the CRP framework.
- Provide specific examples from their industry experience that would help illustrate the constructibility issues involved with specific constructibility functions.

Later, each of the 25 constructibility functions of the CRP framework (Figure 18) was analyzed, based on inputs from the Research Advisory Team, to develop steps required to perform them. This analysis was conducted in a brainstorming exercise. Two to four steps were identified for each function. At this stage, the steps reflected simple statements of actions needed to perform a constructibility function. As input was received from the Research Advisory Team members with respect to function steps, these were modified and revised. Finally, proposed constructibility review tools and their tentative link to each constructibility function were initially established.

The next step was to develop detailed descriptions of each constructibility function. A description would include the following items, based on information represented in the IDEF0 model:

- Description and performance steps of function (function),
- Information needed to perform function (inputs),
- Information provided by performing function (outputs),
- People and tools used to perform function (mechanisms),
- Policy/project constraints that guide use of function (controls),
- Specific examples that illustrate issues/concepts associated with function performance, and
- Discussion of how function performance changes as a result of project policy/constraints (project size, complexity, organizational nature of STAs).

Two- to four-page descriptions were prepared for each constructibility function. All items shown above were detailed in these descriptions. This information was then used to create a preliminary draft of the workbook content. Key information was extracted from the two- to four-page written descriptions. This draft document became the basis for the next Research Advisory Team Review.

The CRP was being developed primarily based on the IDEF0 models. As the framework attained a greater degree of refinement, the need for a corresponding PDP framework became evident. Such a framework would orient users of the CRP toward activities performed in different phases and subphases of project development. A generic PDP framework was developed, as shown in Figure 19, for review by the Research Advisory Team.

The intent of the PDP framework was to show those project development activities that typically occur during the planning, design, and construction phases. This framework can be overlaid onto that of the CRP to show the relationship between project development activities and the constructibility functions that are performed during each project development phase.

A second review was held with the Research Advisory Team. The three objectives of this review were

- To obtain specific content input from members of the advisory team on the preliminary draft of the CRP workbook,

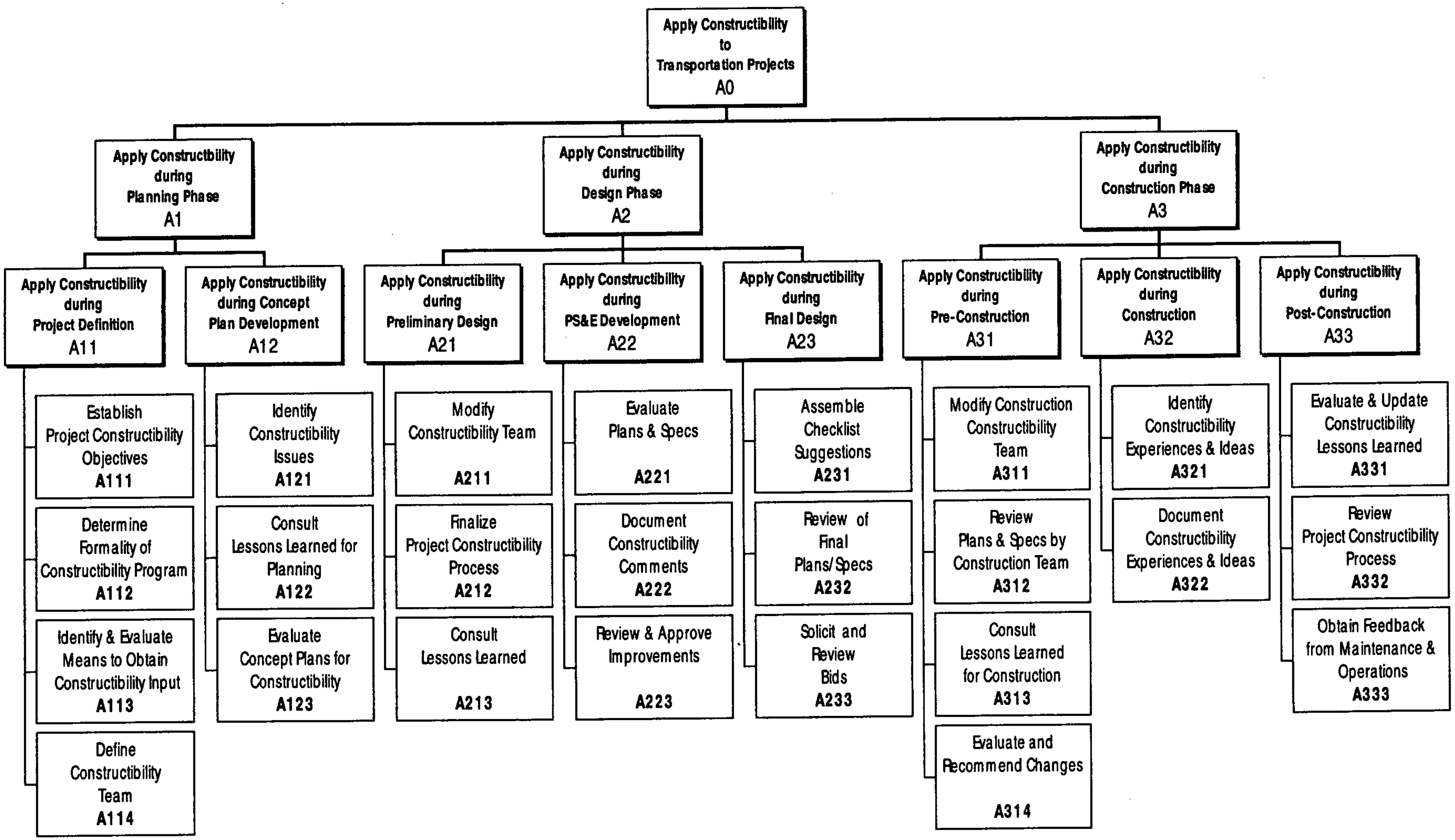

Figure 18. Modified preliminary CRP framework.

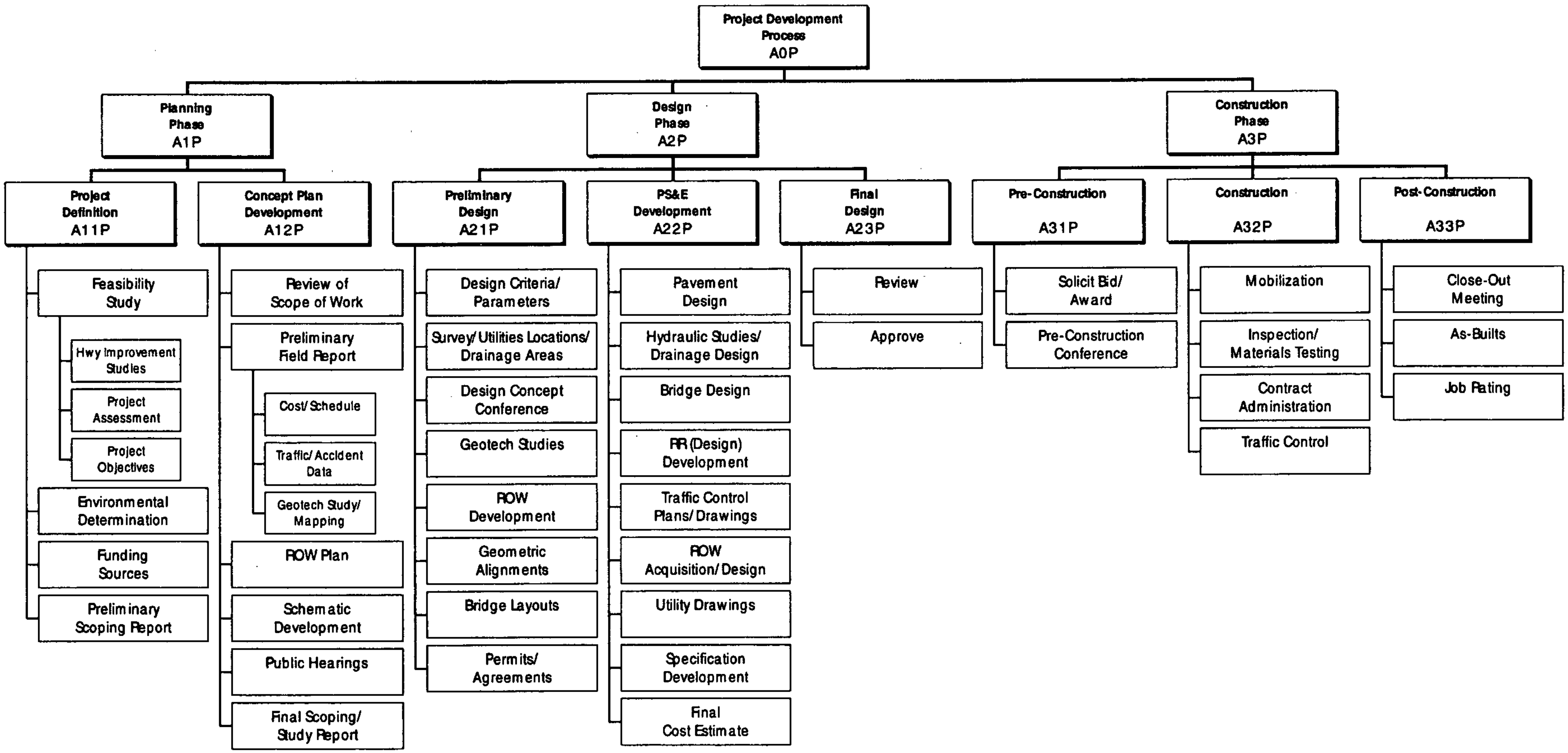

Figure 19. Project development framework.

- To obtain input on the use of review tools for constructibility implementation, and
- To discuss the general workbook approach.

The review was structured to allow members of the team enough time to read draft workbook materials. Then Research Advisory Team members made presentations of their analysis of each assigned section of the draft workbook. Presentations were followed by a general critique of each phase of the CRP.

The PDP framework was also reviewed by the Research Advisory Team. Generic functions (activities) performed during planning, design, and construction were identified for each of these phases. This framework would indicate typical project development activities that occur when performing constructibility functions corresponding to each project development phase. Review tools are discussed in Chapter 7.

General results and conclusions drawn from this review were as follows:

- Slight modifications were recommended to several constructibility functions.
- Better definition of constructibility was needed, including ranges of effort for a standard project with one individual performing constructibility to complex projects using a constructibility team.
- General content was acceptable and accurate.
- The CRP was comprehensive.

One major problem area concerned a step that indicated the possibility of a rebid. This step was highly unlikely to occur and not an area where a constructibility team would be involved. There were several places where project development steps were mixed with constructibility steps. Many minor modifications were suggested to enhance content. Other comments were as follows:

- The document appeared bureaucratic and needed to be simplified by using more tables, figures, and bullets and less running text.
- The workbook should have two distinct parts: an executive summary for DOT decision makers, and CRP guidelines clearly separated for project-level users.
- There was a need to clarify assumptions required for implementation (e.g., some agency support structure in place) and term definitions (e.g., constructibility engineer/coordinator).
- There was a need for practical applications and examples to illustrate concepts, steps, and tools.

The final CRP framework, altered based on these modifications, is shown in Figure 20. The CRP was now comprised of 21 functions, 7 in planning, 7 in design, and 7 in construction. This simplified the CRP and placed the proper emphasis on constructibility during the planning and design phases of the PDP. These changes, when incorporated, finalized the CRP model.

MODEL VALIDATION

The validity of the final CRP model was assessed by applying the process to two typical projects. The Research Advisory Team met with the District Maintenance Engineer, Abilene District, TxDOT, to develop two practical examples of the CRP and test the applicability of the CRP to actual projects. One example was a small project where minimal constructibility analysis was required. The second example was a moderately complex project where an increased level of constructibility analysis was necessary.

The validation process required the research team to, in effect, simulate the actual application of the CRP as if the CRP were being performed as the project was developed. This was necessary because both projects were completed. Also, personnel knowledgeable about these two projects participated in this simulation effort. As each constructibility function was applied, outcomes were documented. Other changes to information relevant to each constructibility function were noted.

The small project was an intersection upgrade described as the Buffalo Gap Intersection. This project cost about $1.6 million and had a project life—from planning to completion of construction—of approximately 20 months once funds became available. The project consisted of a complete intersection upgrade under an existing overpass and modifications to a frontage road.

Using the Buffalo Gap Intersection project, the CRP was applied beginning with the planning phase, then design, and finally to construction. Each constructibility function step was reviewed in detail, including actions and the use of relevant tools. Issues to consider were confirmed and specific outputs relevant to each function were developed for this project. Each function was scrutinized in detail. Changes in steps of functions and tool applications were recommended. Final assessment indicated that the CRP can be successfully applied to a small project.

After this project application, the CRP was modified slightly. Based on results from the first project, the CRP was applied again using a moderately complex project to assess its flexibility as a generic model. The research team met with the District Maintenance Engineer and the Design Engineer, Abilene District, TxDOT, to test this second practical example. The Loop 322 Interchange project was selected. This project was a $16 million construction of a series of two-level overpasses connecting US 83 and US 322 in Abilene, TX. Overall project time from start of planning through construction completion was about 7 years. A full day was spent applying the CRP to this project. Each constructibility function was reviewed and simulated, and suggested modifications to the model were documented.

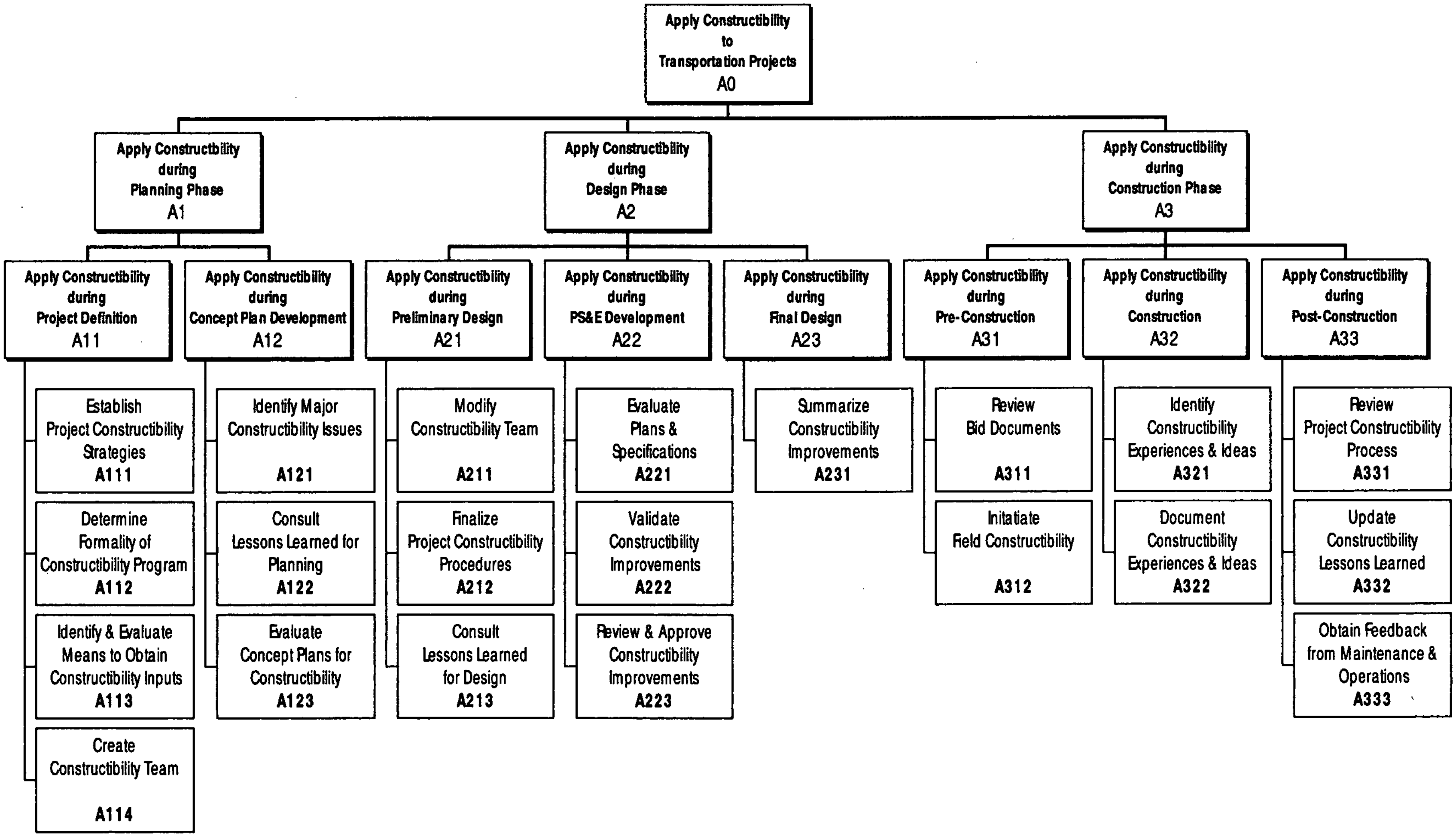

Figure 20. Final CRP framework.

Based on application of the CRP model on two projects and the resulting modifications, the final assessment indicated that the model could be successfully applied to a range of projects. Time did not permit the opportunity to apply the model to a large and very complex project. Although this was a limitation of the model, it is argued that the generic model, with some degree of adaptation, could also be effectively applied to very large and complex projects.

INTEGRATION OF THE CRP AND THE PDP AT THE FUNCTION LEVEL

As shown in Figure 14, a continuous exchange of information occurs between the PDP and the CRP. During the PDP, information exchange is initiated through PDP activities and then is followed by specific applications of constructibility functions. As a typical example, Figure 21 shows this iterative process in more detail as it happens during the project definition subphase. Mechanisms of this process at micro-levels are illustrated in the CRP workbook (*NCHRP Report 391*).

The project scope study or scoping report is the major output of the PDP planning phase. During the project definition subphase of planning, a preliminary project scope study is prepared. This document is completed as a final scoping report during concept plan development. The main focus of constructibility, during the project definition stage, becomes planning for constructibility (Functions A111, A112, A113, and A114 in Figure 21b). This includes determining how constructibility objectives can help achieve project objectives. The level of formality of the program is determined. How constructibility expertise is acquired is addressed, especially in the context of in-house or outsourced design. Finally, the constructibility team is defined. This constructibility plan would be included in the scoping report submitted for approval and incorporation into a multiyear plan. Because constructibility requires monetary expenditures and commitment of other resources, incorporating such a plan for the process ensures the proper availability of these resources.

The development process of the CRP model also uncovered the need to formulate a time line that would show when project development activities/milestones occur during various project phases in relation to when constructibility functions would be performed. This time line would help orient the user to where in project development constructibility constructibility functions are conducted.

As shown in Figure 22, the CRP also serves to bridge discontinuity in the PDP. This illustrates schematically the integration of the CRP with the PDP at different phases and also identifies milestones critical to project development. These milestones delineate transition points during the project life cycle.

The CRP was structured to bridge the gap between phases both to sustain the constructibility process and to provide continuity over the project's life. Implicit in Figure 22 was a time dimension that could vary considerably from project to project. For example, project planning could take several years. Upon submission of the final scoping report, the project is incorporated into a multiyear plan. Actual release of funds for continuation of the project into the design phase may take additional time, depending on the availability of funds and project need. Thus, before design starts there could be a disconnect in time shown by the gaps in Figure 22. This is a reason why developing a constructibility plan during planning could be effective in bridging this time disconnect. The same disconnect, usually lesser in proportion, occurs between design and construction, when the project may have to wait for required funds for construction.

ADAPTABILITY OF THE CRP FRAMEWORK

The CRP was designed to be flexible in order to adapt it to specific project characteristics and requirements. Similarly, the CRP can be modified to be consistent with an STAs approach to project development, policies, and resource availability.

A key driver behind the flexible nature of the CRP is project complexity. Typically, total project cost and total workhour effort reflect a level of complexity. Also, the type of project has a relationship to complexity. Projects located in an urban setting and those involving reconstruction or grade separation are often more complex. Projects that involve many interfaces with other government agencies, the public, consultants, designers and contractors may indicate a higher level of complexity. For purposes of applying the CRP, the following classification of transportation projects was adopted to reflect the level of project complexity. This classification was based on input from the ADOT Constructibility Engineer and the Research Advisory Team.

Standard or Smaller Projects

- Asphaltic concrete overlays,
- Seal/flush coats,
- Guard rail improvements,
- Bridge widening less than 100 ft in length,
- Intersection improvements,
- Rural freeways/highways (new alignment—flat terrain),
- Rural traffic interchanges,
- City street improvements (curb and gutter, resurfacing),
- Climbing lanes (without earthwork),
- Geotech projects (slope laybacks for slide repair or rock fall), and
- Generally smaller projects that do not get extensive review attention.

Moderate to Highly Complex or Larger Projects

- Urban freeways,
- Depressed freeways,

PROJECT DEVELOPMENT PROCESS DURING PROJECT DEFINITION

CONSTRUCTIBILITY REVIEW PROCESS DURING PROJECT DEFINITION

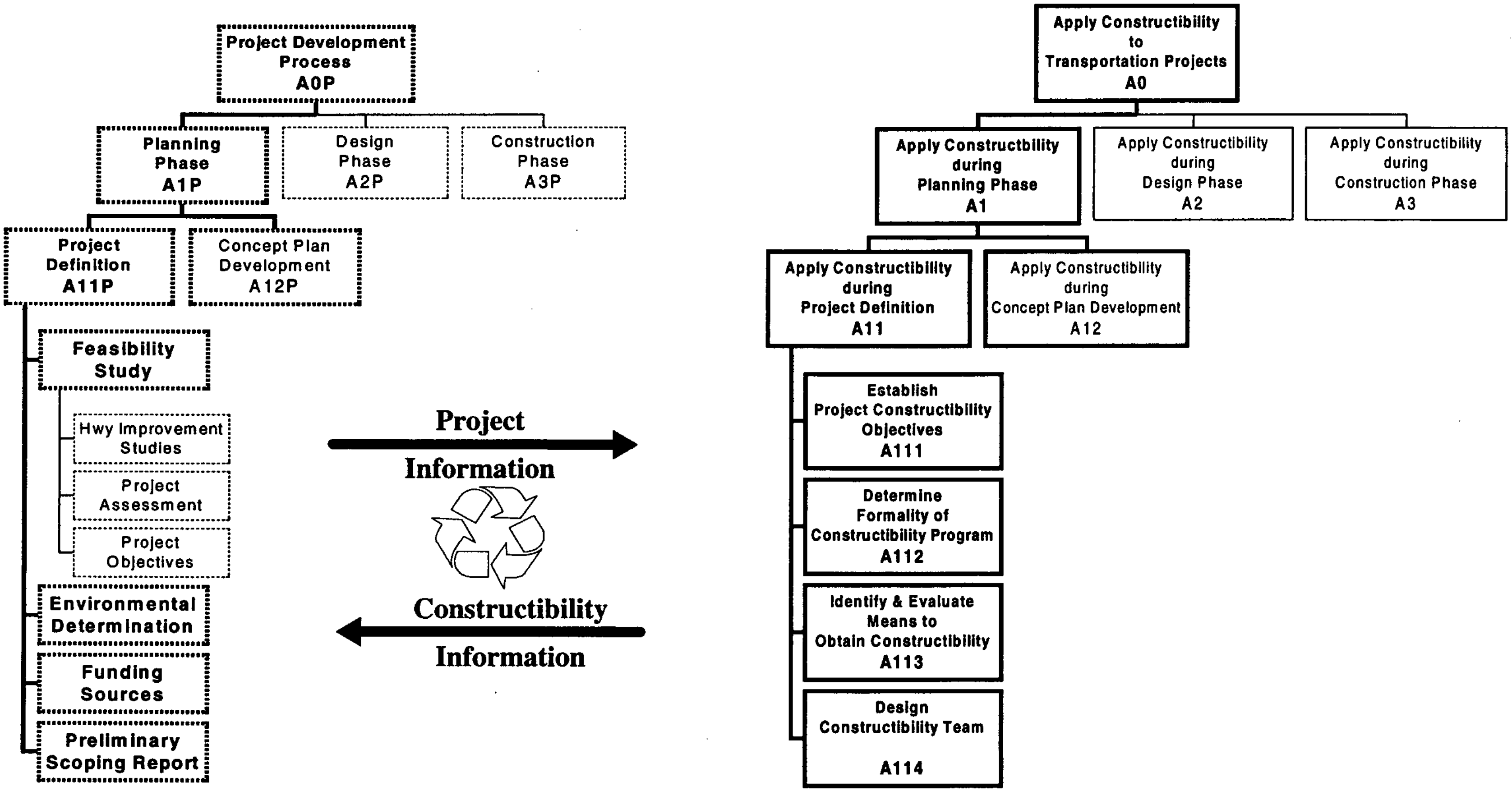

Figure 21. Constructibility during PDP.

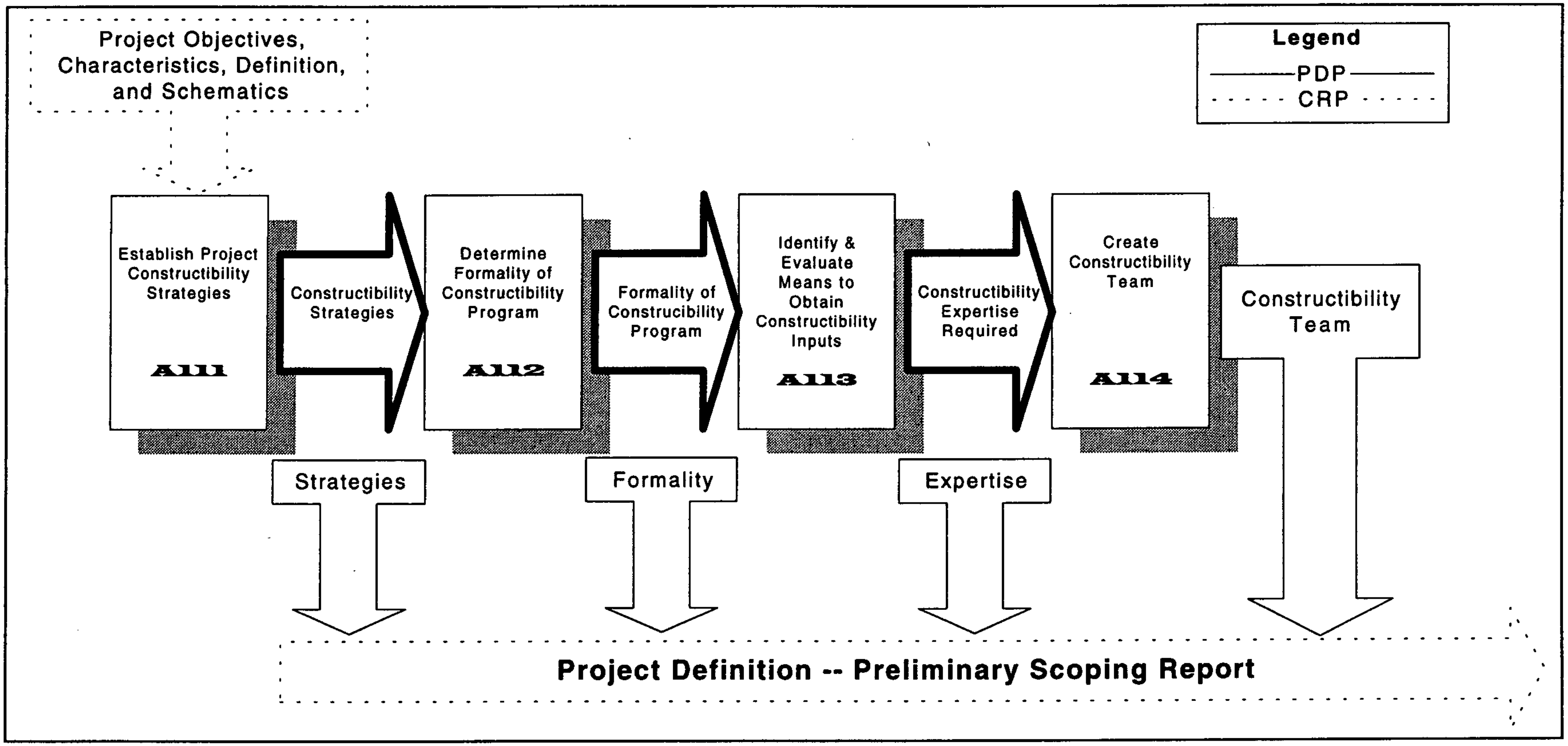

Figure 21. Constructibility during PDP. (continued)

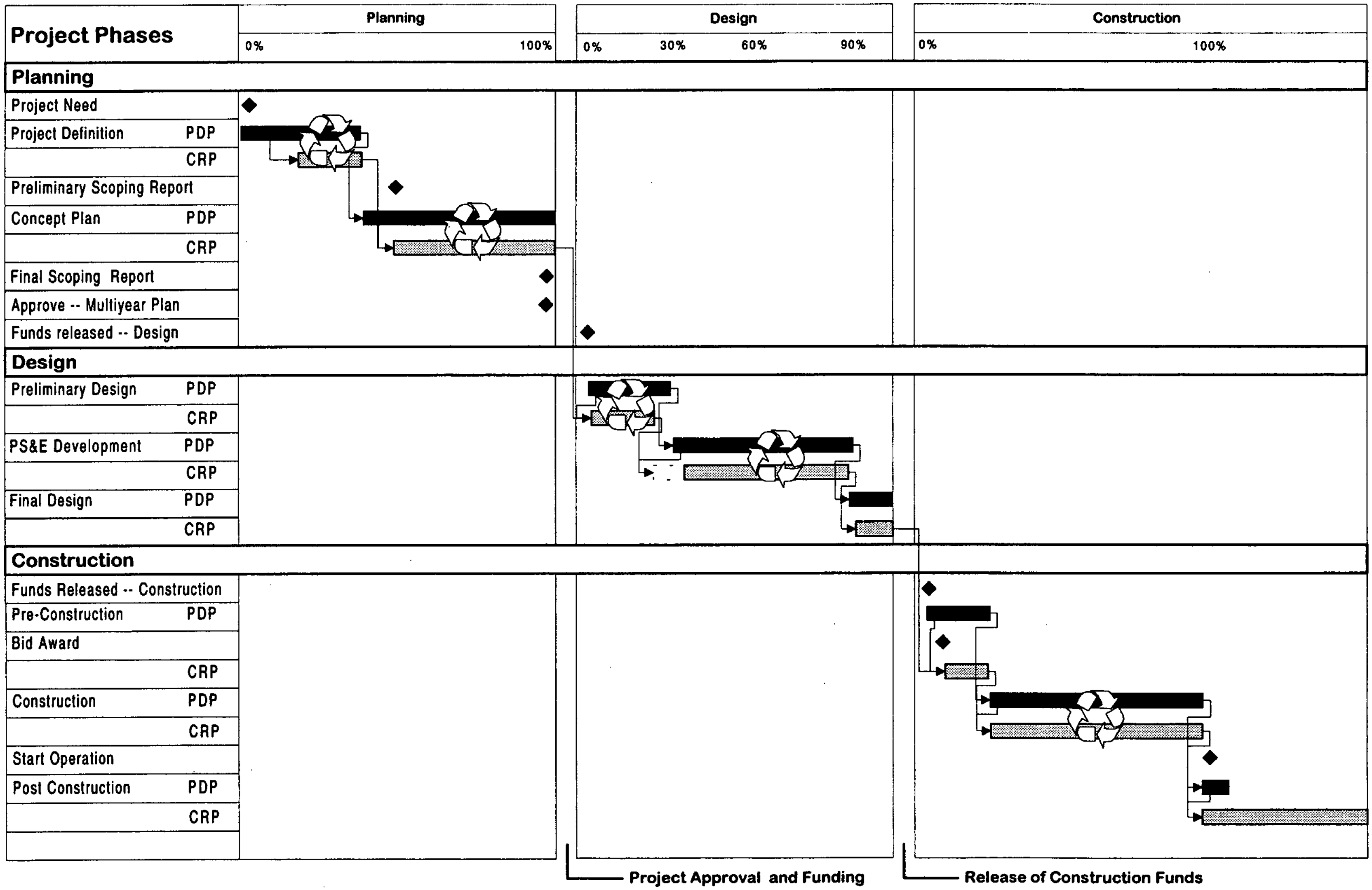

Figure 22. Timing of the CRP with respect to the PDP.

- Bridge widening greater than 100 ft in length,
- Major bridges (new construction),
- Urban traffic interchanges,
- Rural widening or realignment (under traffic),
- Rural freeways/highways (new alignment—mountainous terrain),
- Retaining walls greater than 15 ft in height, and
- City street improvements (underground pipelines).

Increasingly complex projects require more formalized constructibility practices. Based on project complexity, the CRP can be classified into three levels of formality:

- Informal,
- Semiformal, and
- Formal.

The constructibility process has different attributes based on the level of formality. The level of formality helps determine, for example, the resources required for the CRP, frequency of reviews, availability of constructibility resources, assignments of constructibility champion, sources of constructibility information, and constructibility procedures. Thus, the CRP model can fit specific project characteristics and requirements.

WORKBOOK DEVELOPMENT

The Constructibility Review Process workbook (*1*) was developed to present the CRP to senior policy makers and other agency users. By its very nature, the workbook required a high level of process definition. It was conceived within two basic frameworks—those of the CRP and the PDP—and the interaction between them. It was designed to gradually unfold these two interacting processes with increasing levels of detail.

The workbook is composed of two major sections: (1) *Overview* and (2) *Implementation Guidelines.* This approach allows the workbook to sell the concept to senior policy makers and to help project-level users implement the CRP. The Overview comprises three parts answering the why's, what's, and how's of implementing a formalized CRP. The Implementation Guidelines form the main body of the workbook. They illustrate the CRP within the framework of a generic project development process.

Section 1, *Overview,* specifically explains the benefits and the fundamentals of a CRP and discusses the basics of constructibility. Furthermore, this section outlines a process to integrate construction knowledge and experience into the normal work flow during project development. This section also addresses such questions as: *Why* formalize the CRP?; *What* is a CRP?; and *How* is the CRP implemented? The *why* focuses on benefits such as paybacks from constructibility reviews. The *what* overviews the process including steps and review tools available for implementation. The *how* provides guidance on strategies to begin implementation.

Section 2, *Implementation Guidelines,* was designed to be independent of the first section. Figures 23 through 26 illustrate the basic structure of these guidelines starting from the summary level (A0) to the function level. Section 1 is introduced by the initial node of the CRP framework, node A0—*Apply Constructibility to Transportation Projects.* This gives a brief introduction to potential users, so that they can skip the *Overview* section. Following the major phases of the PDP and the CRP framework, the *Implementation Guidelines* are composed of three subsections—planning, design, and construction, which are further analyzed into their respective components until the elemental level (i.e., the functions) are reached. At this elemental level, each constructibility function is described in detail in terms of steps taken, actions performed, tool used, and issues considered. Also, examples are added at the end of each function to illustrate typical outputs of each function and changing outputs as a result of different project types. Additional information is provided as tips, wherever necessary. The workbook appendixes contain a glossary and a detailed discussion on the constructibility tools used in the workbook, as well as the advanced tools that may be used for more developed CRPs (see Chapter 7).

PARADIGM SHIFTS REQUIRED TO IMPLEMENT CONSTRUCTIBILITY

It became apparent during the development of the CRP model that the benefits of the model will not be achieved if certain ingredients are missing at an overall agency level, and if certain mind-sets and certain ways of project execution are not changed. Some specific paradigm shifts are warranted to properly implement constructibility efforts. Paradigm shifts are major "innovative" approaches the agencies will have to address to create the appropriate environment for constructibility implementation. Potential paradigms are discussed in detail in the following section. It is important to note that the majority of the critical issues related to the general project execution process (see Tables 4 and 5) will be solved if these paradigm shifts are endorsed by STAs. They are also considered in developing an implementation strategy.

Existence of Agency Policy for Constructibility

An agency constructibility policy represents the required policies and procedures in the STA that influence the interaction among planners, designers, and contractors, in addition to the overall implementation of a constructibility program. The policy must reflect a commitment to constructibility by senior policy makers. Among others, the policy would stipulate a senior management sponsor or champion of the CRP, allocate funds to support program

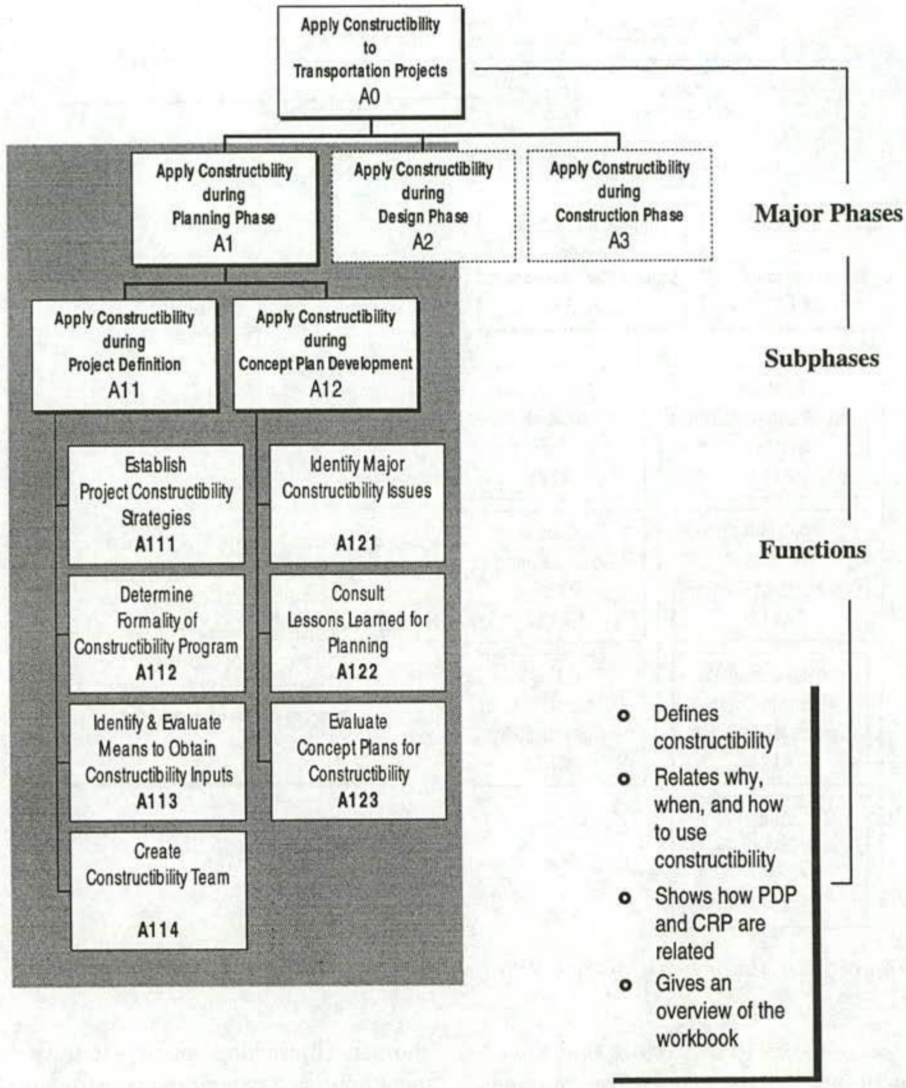

Figure 23. CRP framework.

application, and allocate necessary personnel to successfully conduct the program. This might include providing a position for an agency-level constructibility program coordinator. This policy should be coordinated with other process improvement programs such as NQI, value engineering, and partnering.

Use of Project Constructibility Processes for Planning, Design, and Construction

Besides having senior management commitment and agency support, a project implementation process is necessary for efficient CRP implementation. Many agencies already have improvement programs at the agency level, but lack project implementation for many of these programs, as current practice data demonstrated. The proposed model is a project CRP to assist in the formal application of constructibility principles at the project level. The model has specific functions that allow the project participants to develop the details of constructibility reviews for their unique project. Critical activities, key milestones, and responsibilities of each participant in the CRP for planning, design, and construction are clearly defined.

Recognition of Favorable Benefit/Cost Ratio

Implementation of CRP requires up-front allocation of scarce resources—time, money, and people. Strong evidence indicates, however, that CRP pays for itself by reducing project cost. Prior research indicates that, when methodically implemented, front-end constructibility efforts are investments that result in substantial return. For example, owners in the industrial construction sector experienced an average reduction in total project cost and schedule of 4.3 percent and

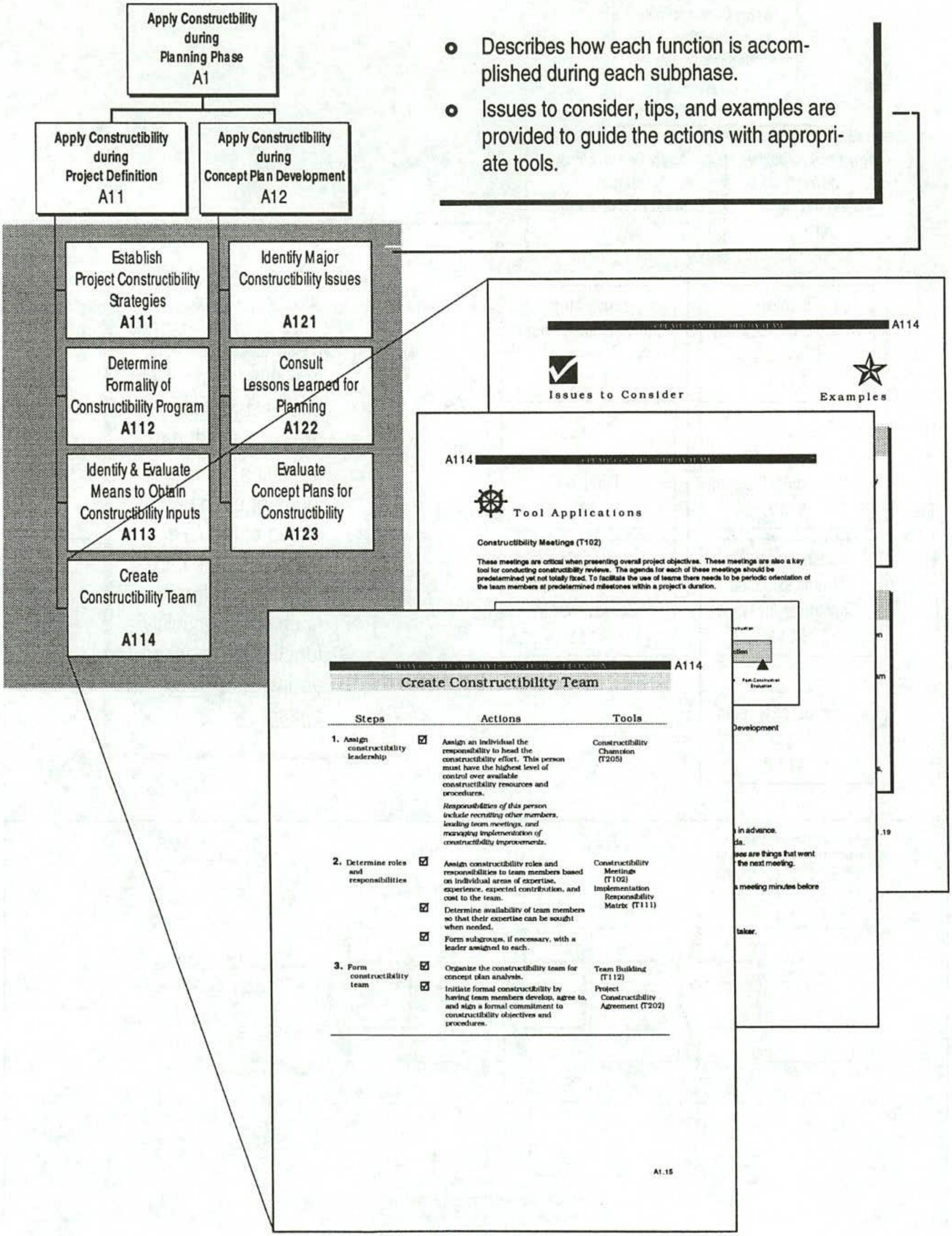

Figure 26. Constructibility functions in subphases.

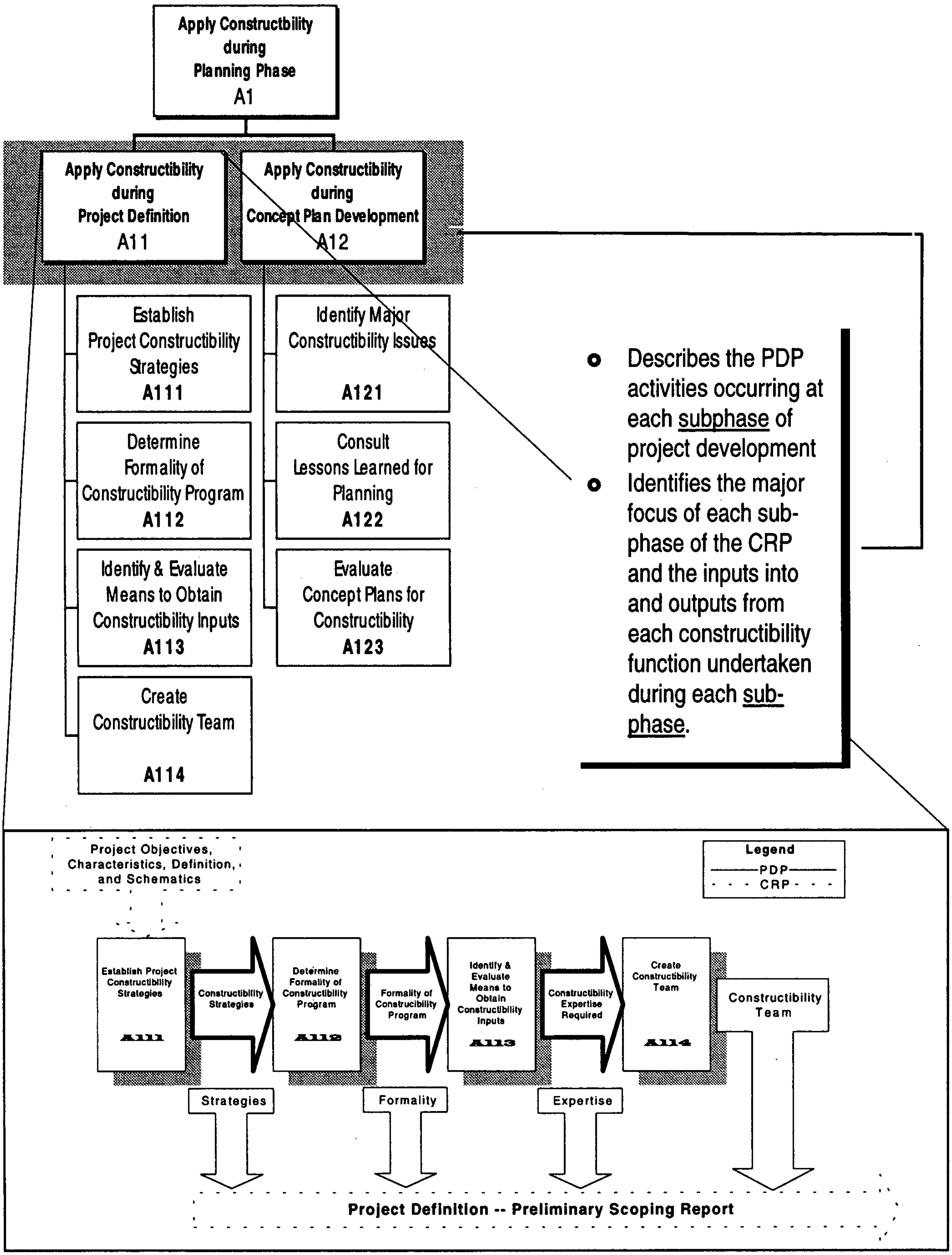

Figure 25. Subphases in a major phase.

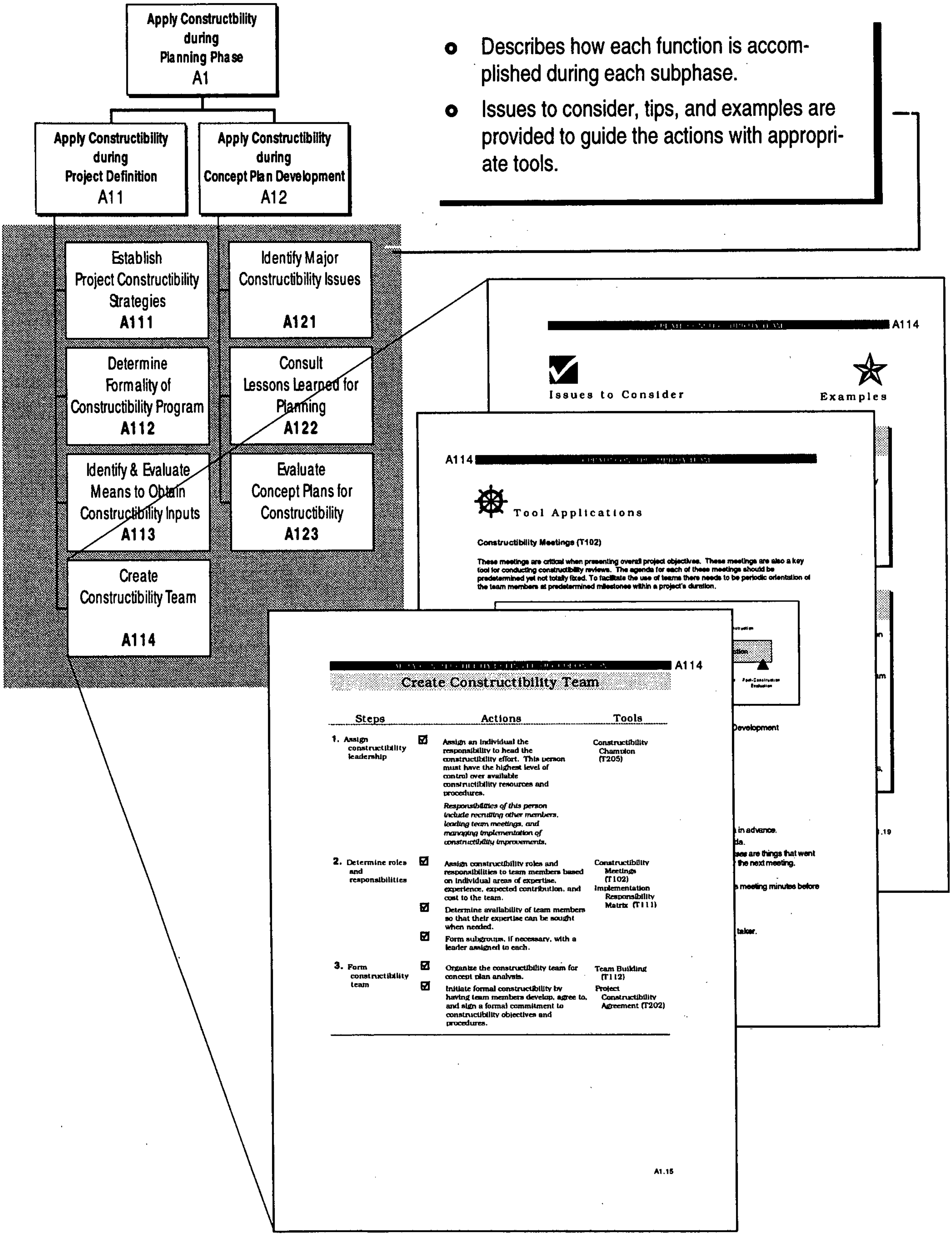

Figure 26. Constructibility functions in subphases.

constructibility consultant/engineer are to supervise the implementation of the CRP and to provide construction expertise and knowledge to designers and planners.

Use of Lessons Learned

The use of lessons learned in the CRP is key to its effective implementation. Lessons learned represent an organized collection of design and construction knowledge and experiences gained from past projects. Construction experience is often lost from one project to the next. The construction industry is a highly dynamic environment where key players in the process change frequently, even within the same project. A mechanism for storing and retrieving critical problems, solutions, knowledge, experiences, recommended changes, and lessons must be implemented by state agencies for them to gain the most benefits from implementing the CRP. An efficient lessons-learned database system will allow personnel from agency district offices, central offices, consulting firm, contractors, subcontractors, and material suppliers access to a broader range of constructibility information. A challenge is to develop a strategy for collecting, evaluating, comparing, entering data, and retrieving it in a timely and efficient manner.

In the CRP, lessons-learned sources are consulted frequently during planning and design and collected throughout construction. Depending on the formality of the constructibility process, mechanisms for implementation could be computerized databases, files, logs, expert systems, and experiences of agency and other project personnel.

Use of Constructibility Implementation Tools

Constructibility implementation tools are a series of tools that would help in the implementation of the CRP. A significant challenge in implementing the CRP is ensuring that project participants perform constructibility steps efficiently and consistently. Therefore, a successful CRP must be accompanied by tools that assist in its application. Tools are provided to help communicate and understand constructibility and to implement and measure constructibility. Computing tools may facilitate ease of implementation. Tools can be specific for constructibility or they could be more generic and only used in a specific manner to support certain constructibility functions.

Use of a Constructibility Team

The use of a constructibility team throughout the project development process is a new concept for the majority of the agencies and firms involved in the transportation industry. This team represents the backbone of implementing the CRP. The team mix will change during design and construction as new participants enter the project. The main responsibility of this team, throughout the project life cycle, is to supervise and implement constructibility reviews. This team, as shown in the CRP model, serves as a key resource in the performance of most constructibility functions.

Enhancing Plans, Specifications, and Contract Documents for Constructibility

The term "enhanced plans and specifications" is a new concept introduced by the constructibility model. Plans and specifications proceed through different stages of development during the life cycle of a project. Enhancement comes when plans, specifications, and contract documents are analyzed for constructibility and appropriate improvements are then included into design documents. These documents are generated as the final design deliverables of the project development process and are used in the construction phase. They serve as a communication tool between designer and contractor personnel.

Poor specifications can cause delays, rework, and claims from misunderstandings, as well as restrict contractor innovation and flexibility (*35*). Enhanced plans and specifications could solve these potential problems by improving the communication of project information between the designers and contractors, thus addressing one major critical issue.

Construction Feedback to Designers

Formalized constructibility feedback to designers on how their design performed in the field is another important aspect of the CRP. This feedback could cover major problems encountered during the construction process; the solutions applied; and positive and negative aspects of the design and their impact on the overall constructibility of the project. Providing feedback to designers will build their personal knowledge base of the impact design decisions have on construction.

Feedback from Maintenance and Operations

Formalized feedback from maintenance and operation personnel is an important aspect of the CRP. The contribution of maintenance and operation personnel in the CRP is invaluable, because they deal directly with the completed facility and understand how well it operates. Input should be continuous during facility performance and should relate to the use of the facility. Methods that could be used for communicating maintenance-related issues include (a) preparing maintenance and operating manuals for complex facilities; (b) making "as-built" plans available to maintenance personnel; (c) having maintenance personnel attend constructibility reviews; and (d) incorporating constructibility information into maintenance manuals (*36*).

CHAPTER 7

CONSTRUCTIBILITY REVIEW TOOLS

INTRODUCTION

An objective of the research was to identify and evaluate existing analytical review tools that can facilitate application of the CRP. To be successful, the CRP needed to identify when, where, and how these tools might be integrated into the review process in terms of the constructibility functions they support. A primary concern was to select tools that could both optimize and improve project cost-effectiveness and information quality through their use in constructibility analysis.

Based on the IDEF0 modeling technique, tools are considered mechanisms that are used to perform a function. In this context, tools are defined as documents, procedures, persons, entities, or software programs. They are used to aid in the communication and implementation of constructibility on a project.

TOOL ANALYSIS

Fifty-two constructibility-related review tools were identified and defined. They were then classified and sorted according to which tools were basic to a CRP and which ones were considered more advanced for an established CRP. The following sections describe this tool development approach.

Tool Identification and Development

The original literature search that was conducted early in this study described "developed or in-progress" computer systems that could directly or indirectly facilitate constructibility gains with proper implementation. This review was performed in a context to determine current practice and to identify critical issues. After a set of constructibility functions was identified, a more focused literature search for tools that support each function was performed. This search provided guidance for finding the most recent and applicable tools among various categories of technology. Twenty-three additional new references were identified. These references are cited in the appendix of the CRP workbook.

The initial tool set for the CRP was selected from all literature reviewed. In the selection process, computer-based tools were originally emphasized because the research problem statement highlighted these as examples: spreadsheets; knowledge-based expert systems; computer-aided design and drafting systems; geographic information systems; databases; and so on. As the formal process model was developed and, as results of the Part I and Part II surveys were analyzed with follow-up interviews, it became apparent that paper-based tools were far more important for implementing a CRP initially. Thus, tools evolved into two categories: (1) paper based; and (2) computer based. Later review by the Research Advisory Team supported this conclusion. Examples of each type of tool are described in Table 6.

Tools were identified on the basis of their ability to be practically implemented, as well as their ability to improve the CRP. Tool practicality was also a consideration for determining when and where in the review process each particular tool should be used. As each of the 52 tools was selected, each was described in a short paragraph. These basic descriptions were enhanced over time with more detail and supporting illustrations and forms.

The integration of tools with constructibility functions was an important step in tool development and required determining when and how each tool would be used in the CRP framework. This analysis was achieved initially by brainstorming and by including input from the Research Advisory Team. As constructibility functions were described in terms of steps and actions, specific tools that would help perform these steps and actions were selected from the set of 52. For example, during the design phase, a tool that could be linked to the constructibility function, *Evaluate Plans and Specifications* (A221), could be a Suggestion Form. An illustration of this form is given in Figure 27. Using a constructibility Suggestion Form allows the constructibility team to capture a potential constructibility idea, comment, or suggestion as an improvement to the design that requires further documentation and analysis before acceptance. Once recorded on the Suggestion Form, benefit/cost analysis might be conducted next on an improvement that has significant potential impact, for instance, on cost, schedule, or user costs. This analysis is performed through the constructibility function, *Validate*

TABLE 6 Example of paper- versus computer-based tools

Type	Tool	Source
Paper-Based	Policy and Objective Statement	WISDOT[10]
Paper-Based	Checklist	FLDOT[8]
Computer-Based	Expert System	CALTRANS[21]
Computer-Based	CD ROM	INDOT[11]

Constructibility Improvements (A222). A second descriptive tool form, Benefit/Cost Analysis, shown in Figure 28, might be used to confirm the true economic viability of an improvement. Finally, if validated, the improvement can be formally documented on an Idea/Lesson-Learned Matrix as illustrated in Figure 29. This improvement can be captured for the project as a checklist item and later for incorporation into an agency-level, lessons-learned database.

The approach as previously described for identifying and linking analytical tools to appropriate constructibility functions was developed for all functions represented in the CRP framework (see final framework in Figure 20). As tool application was studied, the overall flow of constructibility knowledge could be traced through the CRP. This knowledge could be captured using several tools integrated together to develop a lessons-learned process. Figure 30 depicts this linkage for those tools previously discussed and illustrates how lessons learned are collected, analyzed, and stored through the CRP for potential use on future projects.

Tool Classification and Integration

As the integration of tools with functions progressed, the original paper-based and computer-based categories were found to be insufficient for adequate tool classification. Tools were then classified as either Policy/Process-Based Tools or Modeling/Technology-Based Tools. This modification was required because some modeling tools were not necessarily

Constructibility Suggestion Form

Suggestion:____________________________________

Discipline/Craft Affected:____________________________

Description & Illustration:___________________________

Originated By:________________________ Date:________

Project:______________________________________

Assessment of Impact to Project: (to be completed by the Constructibility Coordinator)

Cost:____________________________________

Schedule:_________________________________

Quality:__________________________________

Safety:___________________________________

Engineering:_______________________________

Need to change/update corporate standard specs?______________

Other:___________________________________

Approvals: ______________ ______________

______________ ______________

Comments:__________________________________

____

Figure 27. Example constructibility suggestion form.

Constructibility Suggestion Benefit/Cost Form

Project Name:

Existing Design Description: ______________________________

____

Alternate Design Description: ______________________________

____

Assessment of Cost Impact

Redesign Cost:
- Labor ____________
- Material ____________
- •
- •
- Total ____________

Original Cost:
- Labor ____________
- Material ____________
- •
- •
- Total ____________

Assessment of Benefit Impact to Project:

Cost Savings

Actual (Hard$)
- Labor ____________
- Material ____________
- •
- •

Perceived (Soft$)
- Schedule ____________
- User Savings ____________
- •
- •
- Total Benefit ____________

Figure 28. Example constructibility benefit/cost analysis form.

Issue Code	Lessons Learned	Phase	Function	B/C	Approval		
					Project	Database	Checklist
					☐	☐	☐
					☐	☐	☐
					☐	☐	☐

Figure 29. Example idea/lessons-learned log.

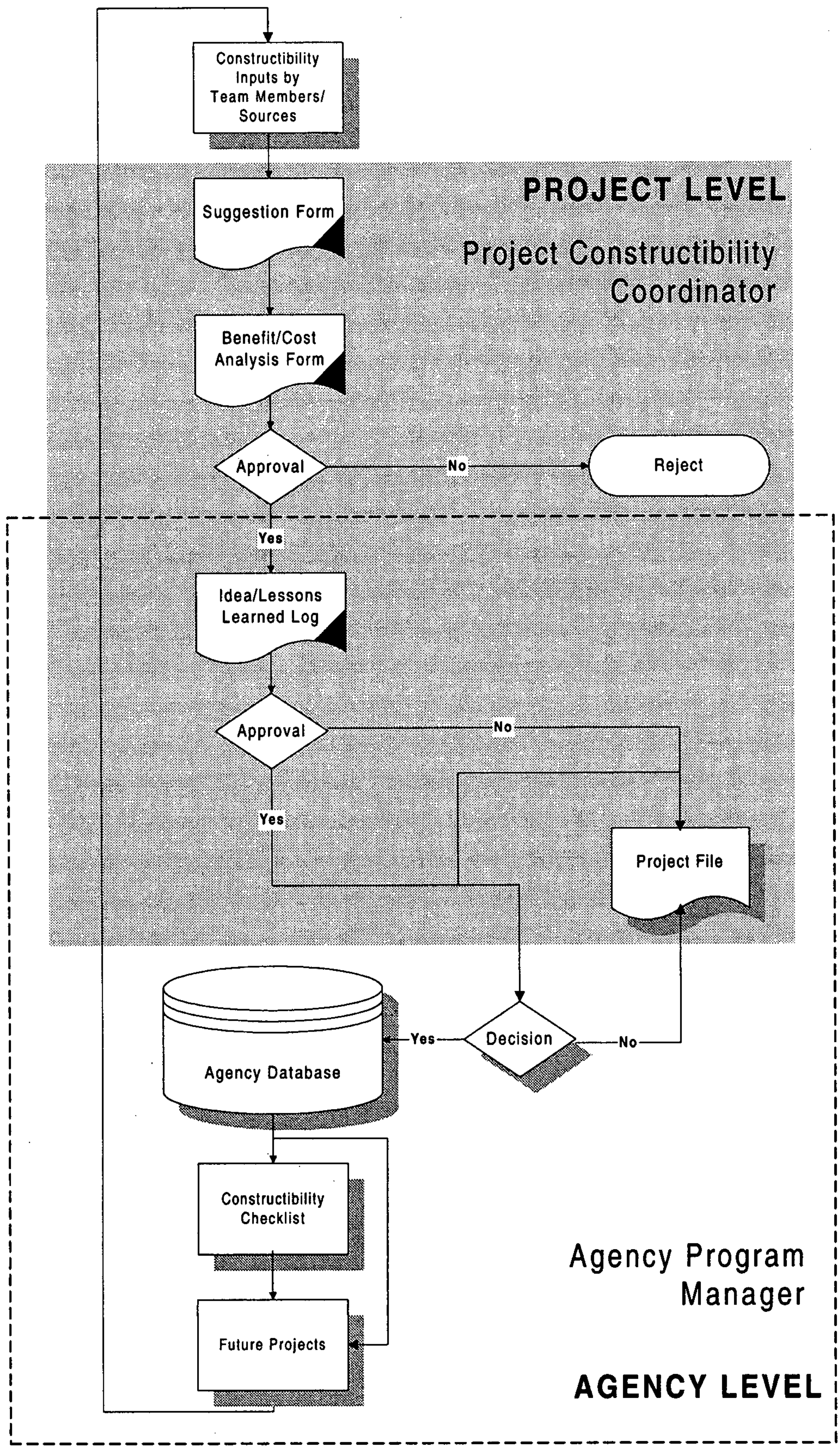

Figure 30. Flow of information.

computer based. Also, tools defined as paper based were mostly policy-driven in nature. As tools were further identified and defined, a trend emerged and resulted in a refined tool classification system as follows: Tools to Understand and Communicate Constructibility (T100s); Tools to Implement and Measure Constructibility (T200s); and Cutting Edge Technology/Computer Tools (T300s). These classifications were considered more intuitive in describing the major thrust of each tool in relation to the CRP. Later sections elaborate on this breakdown.

A formal analysis was conducted to determine which of the 52 tools should be implemented immediately as part of the CRP. This analysis was based upon input from the Research Advisory Team. Members were asked to evaluate each tool using a 1 to 5 scale, according to the following attribute and measurement schemes:

1. Maturity—How developed and utilized is the tool, with 1 being immature and 5 being mature.
2. Ease of Implementation—Is the tool easy to implement based on factors such as user-friendliness, political climate, or organization culture, with 1 being very difficult and 5 being very easy.
3. Maintainability Considerations—Ratings based on whether the tool is easily managed or labor intensive to maintain, with 1 being very difficult and 5 being very easy.
4. Cost of Implementation—Consideration of materials, labor, and support required, with 1 being very expensive and 5 being very inexpensive.
5. Impact on Constructibility Process—Initiation of this tool will impact the success of the CRP, with 1 being low and 5 being high.

These attributes were identified from the literature on the management of technology (*37,38*). Final results included input received from three owners (one federal agency and two state agencies), two contractors (one construction and one design), and one academic. Two state agency members of the Research Advisory Team indicated that not all attributes should carry equal weight. The following weights were agreed upon and used in the analysis:

1. Maturity	15%
2. Ease of Implementation	15%
3. Maintainability Considerations	20%
4. Cost of Implementation	20%
5. Impact on Constructibility Process	30%

These five weights, coupled with the inputs of the research group, provided a weighted average score, including a standard deviation for all tools. These data are presented in Table 7. Analysis of data in Table 7 provided a basis for further dividing the tools into those that were basic for an agency to begin a formalized CRP and those tools that were more advanced. Thus, tools receiving a score of 3.5 or greater, as indicated in Figure 31, were considered basic. As anticipated, most tools in the T100 or T200 group were within the 3.5 and above average score. Twenty-one tools were determined as basic, with the remainder of the tools considered advanced.

Of concern were certain "linking tools" that did not make the 3.5 threshold, such as contract clauses/incentives (T108) that may be tied to value engineering (T206). Other tools that did not make the threshold value that were considered basic included databases (T302), hypermedia (T304), pen-based technology (T4305), and formal processes (T204). These tools were further analyzed for possible inclusion in the CRP as basic tools. Literature reviews and interviews confirmed their importance as key tools. All of them were currently proven by certain agencies as basic, useful tools. Upon completion of the analysis, tool numbers and descriptions were changed slightly and the number of basic tools increased to 27 to include these linking tools that did not make the initial threshold of 3.5.

Twenty-seven selected tools were integrated into the CRP guidelines. This integration concept was transparent to the user, however, because of the user-friendly format developed. This format concentrated on the use of tables, flow charts, and graphics to communicate tool concepts, rather than text. Some text was added to transition from steps and actions to figures. Detailed descriptions of each tool were developed.

In addition to the general classification by tool function (e.g., T100s, T200s, T300s and T4000s), another way of viewing tools was identified. Many tools were strictly used for constructibility purposes, such as the Suggestion Form. Other tools were generic in nature, but could be refocused to aid or assist in effectively implementing constructibility reviews (i.e., partnering).

A final total of 52 tools was identified and classified. Tables 8 through 11 number these tools by the following characteristics: tools to understand and communicate constructibility (T100s); tools to implement and measure constructibility (T200s); cutting-edge constructibility tools (T300s); and advanced/future tools (T4000s), respectively. As shown in Table 11, the T4000 tools have maintained the second digit (i.e., 100, 200, 300) to denote tool function.

TOOL APPLICATION

The list of analytical tools was divided into the 27 suggested and described tools that were considered to be basic for the implementation of a formal CRP. Twenty-five review tools were considered for future use. These advanced or future tools would be considered only by an agency that already had a well-established, formalized CRP. Basic tools were included within the body of the CRP

TABLE 7 Review tool rankings by research advisory team member

	Analysis								
Tool	**Number**	**RAT#1**	**RAT#2**	**RAT#3**	**RAT#4**	**RAT#5**	**RAT#6**	**Avg Score**	**Std Dev**
Policy & Objective Statements	T101	3.2	5	5	3	5	5	4.4	0.98
Team Orientation Meetings	T102	3.8	5	4.6	3.85	3.65	5	4.3	0.62
Operations & Maintenance Input	T103	4.65	5	4.45	3.05	0	5	3.7	1.95
Project Team Organization Structure	T104	4.35	3	4.1	3.65	2.5	5	3.8	0.91
Idea Logs	T105	3.6	4.2	4.15	4.8	3.3	3.8	4.0	0.53
Pre-Bid Conference	T106	4.5	5	3.3	3.2	2.7	5	4.0	1.01
Pre-Construction Conference	T107	5	5	5	3.2	3.45	5	4.4	0.87
Contract Clauses/Incentives/Strategy	T108	3.75	1.85	4.4	2.75	2.35	5	3.4	1.23
Partnering	T109	4.5	3	4.3	3.75	3.3	5	4.0	0.76
Contractor-Determined Schedules	T110	4.4	4.6	5	2.4	2.35	4.3	3.8	1.16
Implementation Responsibility Matrix	T111	4.8	2.35	2.5	5	3.7	4.4	3.8	1.15
Team Building	T112	3.25	2.95	4.1	3.85	2.75	5	3.7	0.84
Technical Managers & Constructibility Engineers	T113	4.45	4.55	4.5	3.6	2.9	4.6	4.1	0.70
Post-Construction Reviews/End-Contract Write-ups/As-Built Updates	T201	3.35	3.7	4.1	3.45	3.3	5	3.8	0.65
Evaluation Matrices	T202	2.55	1.7	4	5	3	3.55	3.3	1.15
Checklists	T203	4.3	4.7	4.3	3.4	4.4	5	4.4	0.54
Formal Processes	T204	3	0	3.3	0	2.6	0	1.5	1.64
Project Champions/Management Support	T205	4	3	5	3.65	2.95	5	3.9	0.92
Value Engineering	T206	3.8	2.75	3.3	3.75	2.75	4.6	3.5	0.71
Constructibility Lessons-Learned Matrix	T207	3.35	1.6	4	3.6	3.3	5	3.5	1.11
CPM	T208	3.15	3.2	4.1	3.2	2.95	5	3.6	0.79
Cost/Benefit Analysis	T209	5	3.8	5	3	2.55	4.4	4.0	1.03
Outside Sources	T210	4.8	3.35	4.3	3.6	2.1	5	3.9	1.08
CAD/Animation/GCCA	T301	3.45	3.3	5	2.65	2.6	4.6	3.6	1.00

TABLE 7 **Review tool rankings by research advisory team member** (*continued*)

Databases/Object Oriented	T302	2	1.5	2.8	2.7	3.45	4.3	2.8	1.00
GIS/Graphical Modeling/Digital Imaging	T303	3	1	3.8	3.3	1.95	4.45	2.9	1.26
Hypermedia/Multimedia/CD-ROM/ Hypertext	T304	3.15	1	3.55	3.6	3.45	4	3.1	1.08
Influence Diagramming	T4114	1.85	1	3	3	0.6	4.4	2.3	1.43
HOT Diagramming	T4115	3.85	1	3.4	2.7	2.65	0	2.3	1.47
Storybook Management	T4116	4.15	1	3	1.5	2.7	5	2.9	1.52
Design/Build Approach	T4211	4	0	3.5	3.8	2.05	5	3.1	1.78
Concurrent Engineering	T4212	1.6	1	2.3	2.45	2.5	4.65	2.4	1.24
Decision Trees	T4213	3.65	1	3.85	3	3.35	5	3.3	1.32
Root Cause Analysis	T4214	2.15	2.7	4.1	2.35	2.85	5	3.2	1.12
Regression Analysis	T4215	1.7	1	3.8	2.35	1.85	4.4	2.5	1.31
Forecasting Models	T4216	2.5	1	3.85	0	2.3	3.5	2.2	1.47
Sensitivity Analysis	T4217	3.15	1	3.5	2.35	2.4	4.7	2.9	1.25
Process Modeling	T4218	1.5	2	4.3	3	3	5	3.1	1.33
Multiple Criteria Decision Making	T4219	1.85	1	3.3	3	2.45	3.8	2.6	1.02
Financial Modeling	T4220	2.2	3.15	4	0	0	3.5	2.1	1.76
Linear Programming	T4221	1.7	1	3.8	2.7	2.65	3.35	2.5	1.04
EDI/Bar-Coding/Pen-Based Technology	T4305	3	1	3.6	4.15	2.5	4.4	3.1	1.25
Simulation	T4306	2.35	1	3.8	2.7	2.8	4.4	2.8	1.18
Case-Based Reasoning	T4307	3.2	1	4.2	2.3	3.5	4	3.0	1.20
GPS Technology	T4308	3.6	1	4.3	3.3	2.6	4.1	3.2	1.21
Expert Systems/Rule-Based Reasoning	T4309	3.65	1	2.7	2.7	2.15	2.75	2.5	0.88
Visual Spreadsheets	T4310	2.65	1	4.4	2.7	2.7	4.65	3.0	1.34
Virtual Reality	T4311	1.95	1	3	2.2	2.45	3.8	2.4	0.95
Fuzzy Logic	T4313	1.5	1	3	3	1.8	1.75	2.0	0.82
Neural Networks	T4313	1.95	1	2.7	3	0	2.6	1.9	1.16
Visual Interactive Modeling/VIM Simulation	T4314	2.45	1	4	2.2	1.65	3.95	2.5	1.22
Voice Recognition	T4315	3.3	1	4.6	3.6	1.7	2.45	2.8	1.32

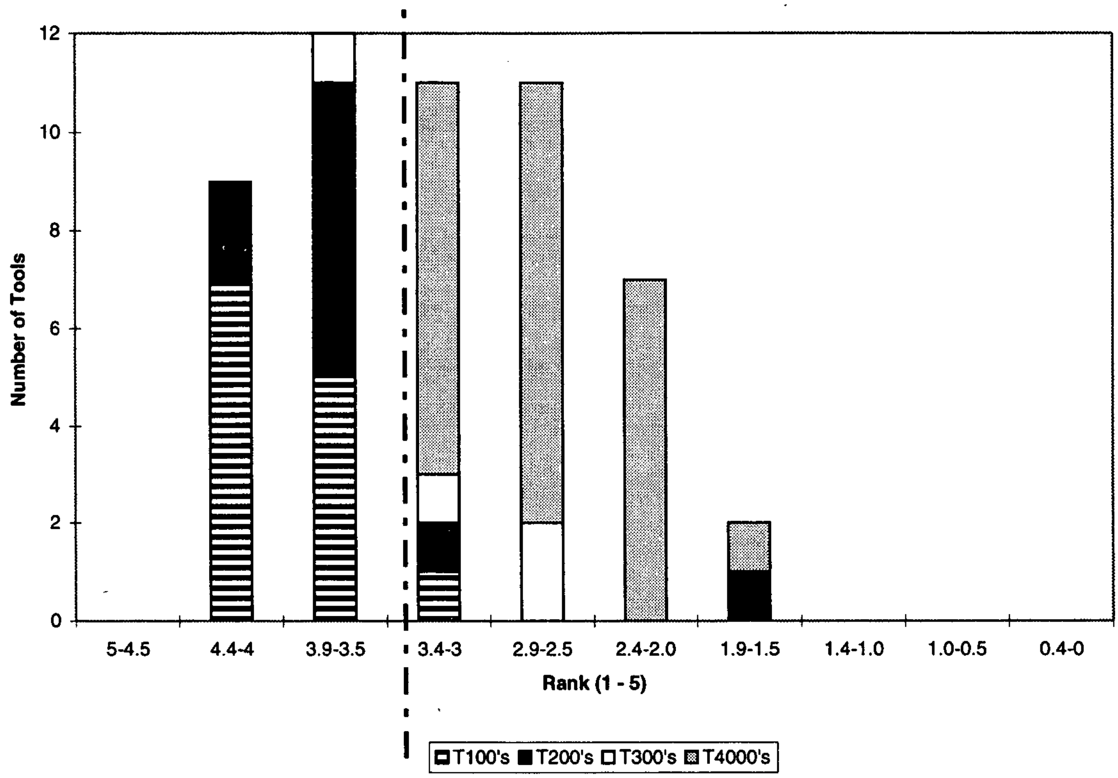

Figure 31. Ranking of potential review tools.

TABLE 8 Tools to understand and communicate constructibility

CODE	TOOLS
T101	Policy and Objective Statements
T102	Constructibility Meetings
T103	Operations and Maintenance Input
T104	Constructibility Organization Structure
T105	Suggestion Form
T106	Pre-Bid Conference
T107	Pre-Construction Conference
T108	Contract Clauses/Incentives
T109	Partnering
T110	Contractor-Determined Schedules
T111	Implementation Responsibility Matrix
T112	Team Building
T113	Constructibility Engineers

TABLE 9 Tools to implement and measure constructibility

CODE	TOOLS
T201	Post-Construction Reviews
T202	Project Constructibility Agreement
T203	Checklists
T204	Formal Processes
T205	Constructibility Champion
T206	Value Engineering
T207	Idea/Lessons-Learned Matrix
T208	Critical Path Method
T209	Benefit/Cost Analysis
T210	Constructibility Sources

TABLE 10 Cutting-edge technology and computer tools

CODE	TOOLS
T301	CAD /GCCA
T302	Databases
T303	Hypermedia/Multimedia/CD-ROM/Hypertext
T304	EDI/Bar-Coding/Pen-Based Technology

workbook with a detailed description of these tools in appendix B.I of the workbook. Future tools were not included within the body of the workbook, but they are described in appendix B.II.

Tool descriptions were taken from the literature search that was conducted both early in the research and as an initial part of formal tool development. As indicated earlier, analytical tools were linked to CRP functions and presented in a user-friendly format. The workbook includes a tabular link (see Figure 32), applications, descriptions, and tips (see Figure 33) for each basic tool. Appendix B.II includes a description (see Figure 34) and application tips (see Figure 35) for each future tool. Appendixes B.I and B.II of the workbook also contains roadmaps indicating when (which constructibility functions) tools should be used in the CRP. These are shown in Figures 36 and 37.

Appendix B of the workbook also includes a comprehensive bibliography. This bibliography is cited by tool number for easy cross-referencing, so that users can obtain additional assistance on a specific tool, as needed. The bibliography contains the 23 new references that were identified after the CRP functions were defined, and as part of tool identification and function linking.

TABLE 11 Future tools for implementation

CODE	TOOLS
T4114	Influence Diagramming
T4115	HOT Diagramming
T4116	Storybook Management
T4211	Design/Build Approach
T4212	Concurrent Engineering
T4213	Decision Trees
T4214	Root Cause Analysis
T4215	Regression Analysis
T4216	Forecasting Models
T4217	Sensitivity Analysis
T4218	Process Modeling
T4219	Multiple Criteria Decision Making
T4220	Financial Modeling
T4221	Linear Programming
T4305	GIS/Graphical Modeling/Digital Imaging
T4306	Simulation
T4307	Case-Based Reasoning
T4308	GPS Technology
T4309	Expert Systems/Rule-Based Reasoning
T4310	Visual Spreadsheets
T4311	Virtual Reality
T4312	Neural Networks
T4313	Fuzzy Logic
T4314	Visual Interactive Modeling/VIM Simulation
T4315	Voice Recognition

APPLY CONSTRUCTIBILITY DURING PROJECT DEFINITION

A114

Create Constructibility Team

Steps		Actions	Tools
1. Assign constructibility leadership	☑	Assign an individual the responsibility to head the constructibility effort. This person must have the highest level of control over available constructibility resources and procedures. *Responsibilities of this person include recruiting other members, leading team meetings, and managing implementation of constructibility improvements.*	Constructibility Champion (T205)
2. Determine roles and responsibilities	☑	Assign constructibility roles and responsibilities to team members based on individual areas of expertise, experience, expected contribution, and cost to the team.	Constructibility Meetings (T102) Implementation Responsibility Matrix (T111)
	☑	Determine availability of team members so that their expertise can be sought when needed.	
	☑	Form subgroups, if necessary, with a leader assigned to each.	
3. Form constructibility team	☑	Organize the constructibility team for concept plan analysis.	Team Building (T112)
	☑	Initiate formal constructibility by having team members develop, agree to, and sign a formal commitment to constructibility objectives and procedures.	Project Constructibility Agreement (T202)

A1.15

Figure 32. Constructibility function with integrated tools.

Tool Applications

Constructibility Meetings (T102)

These meetings are critical when presenting overall project objectives. These meetings are also a key tool for conducting constructibility reviews. The agenda for each of these meetings should be predetermined yet not totally fixed. To facilitate the use of teams there needs to be periodic orientation of the team members at predetermined milestones within a project's duration.

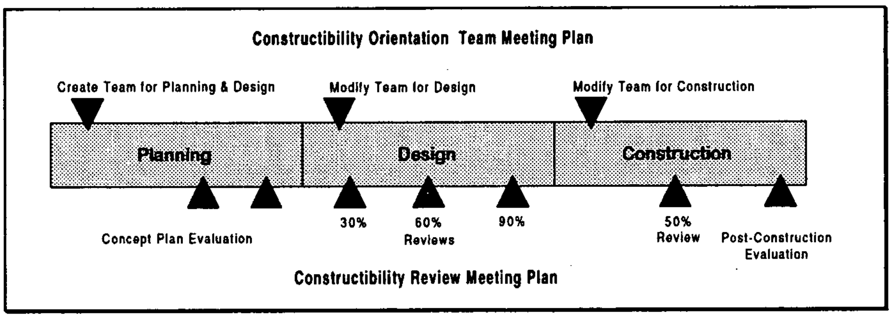

FIGURE A114.1
Typical Schedule for Constructibility Meetings during Project Development

Tips

Effective Meeting Guidelines

- Establish the **agenda** — The team leader should publish the agenda in advance.
- Establish an **issue board** for items that arise but are not on the agenda.
- Use the **plus/delta** technique to continue improving meetings — *pluses* are things that went well during the meeting and *deltas* are changes that will improve for the next meeting.
- Start **on time**.
- **Be prepared** — Bring required documents to meeting, read previous meeting minutes before meeting, and complete action items for the meeting.
- Invite the **right people** to the meeting.
- Use a **facilitator** at the meeting.
- During the meeting, appoint a **scribe,** a **timekeeper**, and a **minutes taker**.

Figure 33. Constructibility function with tool applications.

Virtual Reality (T4311)

Virtual reality is any model or representation of physical experiences which are conveyed through a different media. This model can be expressed through more than one media at a time, i.e.. sight, sound and even touch. With the aid of computer technology we have the ability to model the real world and replay these sensations, allowing individuals to experience the physical world through artificial stimuli. Virtual reality allows individuals to perform tasks without actual physical changes to occur in the model. This allows physical activities to be optimized before any physical alterations are performed. Through the use of virtual reality devices, organizations can optimize designs for ease of construction. This technology allows for hands on training of workers and the ability to practice difficult operations before performing them in the field. Virtual reality devices can be as simple as a two dimensional program on a screen, similar to a video game; or as advanced as a holographic three dimensional image with mechanical devices attached to the body which place pressure that simulates the physical sensations associated with the image.

Figure 34. Example description of future tool.

Initiate Field Constructibility (A312) — In reviewing plans, specs, and procedures during the construction phase, once again influence diagrams (T4114) can be used to develop and communicate the improvement ideas that result from this process by identifying the decision variables (both certain and uncertain), the uncontrollable variables (both deterministic and random), and the outcome variables. When implementing the recommended field changes from preconstruction review, linear programming (T4221), financial modeling (T4220), and other forecasting models (T4216) can be used to analyze, justify, and implement the variables that have been identified through influence diagramming. A sensitivity or "what if" analysis (T4217) can be performed on the cost/benefit analysis. Computer simulation (T4306) can be applied at this stage, to model these variables and fuzzy logic (T4313) to simulate uncertain events. Because at this stage, the design is complete, field operations can be simulated graphically, using visual spreadsheets (T4310), virtual reality (T4311), GIS (T4305), or visual interactive modeling (T4314).

Figure 35. Example application tip for future tool.

Name of Tool		A111	A112	A113	A114	A121	A122	A123	A211	A212	A213	A221	A222	A223	A231	A311	A312	A321	A322	A331	A332	A333		
		Constructibility Functions																						
Policy & Objective Statements	T101	X				X				X													S	PROD
Constructibility Meetings	T102				X			X		X		X					X						S	PROC
Operations & Maintenance Input	T103							X														X	S	PROD
Constructibility Organization Structure	T104									X							X					X	S	PROD
Suggestion Forms	T105							X				X					X						S	PROD
Pre-Bid Conference	T106															X							G	PROC
Pre-Construction Conference	T107																X						G	PROC
Contract Clauses/Incentives	T108															X							G	PROD
Partnering	T109								X								X						G	PROC
Contractor-Determined Schedules	T110																X						G	PROC
Implementation Responsibility Matrix	T111				X					X							X					X	S	PROD
Team Building	T112				X				X														G	PROC
Constructibility Engineers	T113			X			X		X		X						X						S	PEOP
Post-Construction Reviews	T201						X				X									X			G	PROC
Project Constructibility Agreement	T202				X					X							X						S	PROD
Agency Constructibility Checklists	T203											X									X	X	S	PROD
Formal Processes	T204		X							X													S	PROD
Constructibility Champion	T205				X																		S	PEOP
Value Engineering	T206								X								X						G	PROC
Idea/Lessons-Learned Log	T207							X					X						X	X		X	S	PROD
Critical Path Method	T208							X				X											G	PROD
Cost/Benefit Analysis	T209							X					X				X						S	PROD
Constructibility Resources	T210			X			X		X		X						X						S	PEOP
CAD/GCCA	T301							X				X											S	PROC
Databases	T302						X				X										X	X	S	PROD
Hypermedia/Multimedia/CD-ROM/Hypertext	T303						X				X	X							X				S	PROD
EDI/Bar-Coding/Pen-Based Technology	T304																		X			X	G	PROC

LEGEND

S — specific
G — generic
PROC — Process
PROD — Production
PEOP — People

Figure 36. Tool and function roadmap for workbook tools.

Constructibility Functions

Name of Tool		A111	A112	A113	A114	A121	A122	A123	A211	A212	A213	A221	A222	A223	A231	A311	A312	A321	A322	A331	A332	A333	
Influence Diagramming	T4114							X				X					X					X	PROD
HOT Diagramming	T4115	X				X				X													PROD
Storybook Management	T4116										X									X			PROD
Design/Build Approach (Alternate Contracting)	T4211	X																					PROC
Concurrent Engineering	T4212	X							X														PROC
Decision Trees	T4213																			X			PROD
Root Cause Analysis	T4214																	X					PROD
Regression Analysis	T4215															X							PROD
Forecasting Models	T4216							X								X							PROD
Sensitivity Analysis	T4217												X				X		X				PROD
Process Modeling	T4218																		X		X		PROD
Multiple Criteria Decision Making	T4219																			X			PROD
Financial Modeling	T4220							X					X				X		X				PROD
Linear Programming	T4221												X				X		X				PROD
GIS/Graphical Modeling/Digital Imaging	T4305																						PROC
Simulation	T4306							X				X					X						PROC
Case-Based Reasoning	T4307						X				X									X			PROD
GPS Technology	T4308															X							PROC
Expert Systems/Rule-Based Reasoning	T4309		X				X				X									X			PROD
Visual Spreadsheets	T4310												X				X		X				PROD
Virtual Reality	T4311											X					X						PROC
Neural Networks	T4312											X									X		PROD
Fuzzy Logic	T4313											X					X						PROD
Visual Interactive Modeling/VIM Simulation	T4314											X					X						PROC
Voice Recognition	T4315																					X	PROD

LEGEND
PROC — Process
PROD — Production

Figure 37. Tool and function roadmap for future tools.

CHAPTER 8

IMPLEMENTATION PLAN

INTRODUCTION

A requirement of this research effort was to provide an implementation plan for applying the CRP within STAs, identifying both the effort and resources required to implement the process. Figure 38 illustrates typical steps for an implementation strategy. The first box, "recognize need," is addressed through this NCHRP Project 10-42.

TOOL DEVELOPMENT

The CRP workbook (*1*) is the main tool developed to assist STAs in implementing project-level constructibility reviews (see the second box in Figure 38). Specifically, functions, steps, actions, and tools essential to conduct a formal, comprehensive project-level CRP are presented in the workbook. Using information from the PDP, the CRP provides constructibility improvements that can be incorporated into planning and design documents. The CRP is generic in format and can be tailored to meet characteristics of different project types and agency-level approaches.

MARKETING

Table 12 lists actions that address the marketing of the CRP workbook. Table 12 indicates the number of presentations and papers that either have been or will result from marketing throughout the research project.

One key marketing strategy was to develop and conduct a training workshop for STAs. As shown in Table 12, this effort occurred in two phases: (1) a pilot workshop for the Kentucky DOT and (2) a training workshop for all STAs in Albuquerque, NM. These workshops disseminated the method for integrating the project CRP workbook into agency PDPs. This was accomplished through an example project, applying workbook techniques for constructibility reviews from planning through design and into construction. Benefit/cost issues and implementation barriers were included as part of the workshops. Workshop presenters included a mixture of industry professionals and academics. Also, the workshop format included interactive breakout sessions to engage participants in the actual application of the CRP.

The first workshop was sponsored by the Kentucky DOT (KDOT). Some 45 attendees representing KDOT, consultants, and contractors participated. The second workshop was sponsored by NCHRP Project 10-42. The estimated number of participants was about 75, including instructors, panel members, and STA representatives. STA participants included professionals from planning, design, and construction.

KNOWLEDGE TRANSFER

Integrating construction knowledge and experience into the PDP is a complex process. This integrating action involves many disciplines in order to examine a multitude of potential construction issues often encountered during the planning and design of a facility. The workbook offers a formal CRP to assist STAs in implementing constructibility.

Initially, a few pilot projects should be selected as a test. Pilot projects, initiated under the auspices of a senior management directive, are invaluable in this respect. Although not essential at the outset, an agency-level constructibility support structure is indispensable to sustain implementation.

Long-term or complex bureaucracies are not needed to implement the CRP. Constructibility works best when it is simply an accepted way of doing business with self-evident benefits. Simply stated, *initial* implementation of constructibility neither requires additional people nor additional departments. Implementation will require, however, awareness training of the agency personnel who will implement the CRP, beginning with senior management. This training must focus on basic objectives, methods, and concepts of constructibility. A team approach may best support commencing a new effort, especially when considering the multidisciplinary focus of constructibility. Several strategies for implementation are recommended next. Each agency is encouraged to identify other innovative strategies for implementation.

Project Strategies

Three basic ways to implement the CRP at the project level are as follows:

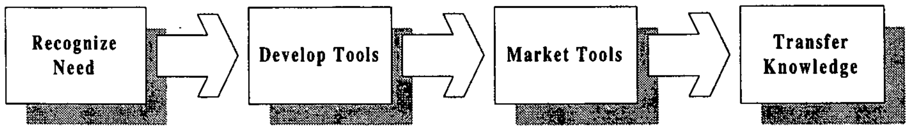

Figure 38. Implementation steps.

1. Start at the beginning of design on a standard to moderately complex project where design is performed in house.
2. Start at the beginning of design on a standard to moderately complex project where design is performed by a consultant.
3. Start at project inception with planning and proceed through the entire CRP on a small project where all planning and design are performed in house.

1. In-house design—Because most STAs perform constructibility informally during the design phase of project development, an excellent starting point to apply a formalized CRP is during preliminary design. The design process is well understood here so communication may be easier. Although the full benefits of the CRP may not be realized, considerable cost savings can be achieved during design (a benefit to cost ratio of 25:1). As successful implementation occurs, the CRP can eventually be integrated into the planning and construction phases of the PDP.

A moderately complex project, such as the Loop 322 Interchange project used in the workbook, should be selected prior to start of design. In the absence of a project constructibility plan formulated in the planning phase, one must be developed early in the design phase. As shown in Figure 39, this plan would entail both the formation of a constructibility team and determination of project-specific constructibility procedures. At this time, some additional effort is required to determine constructibility strategies, level of formality, and resources required. Decisions are made on frequency and timing of reviews, level of documentation desired, and roles and responsibilities of the constructibility team. Documentation of constructibility improvements should occur as the remaining constructibility functions of the CRP are applied during project design. This will help track results of the constructibility effort and provide input for future projects.

2. Outsourced design—Another alternative for implementing the CRP is to start in the design phase of a project that is being designed by a consultant. Agency and consultant personnel would have to participate actively in the constructibility process. A project constructibility coordinator would be needed. This coordination effort could be out-

TABLE 12 Past, present, and future activities

Activity	Presentation	Paper	1995				1996				1997			
			1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
32nd Annual Paving & Transportation Conference Albuquerque, NM	2	2	×											
AASHTO Highway Subcommittee Williamsburg, VA	1				×									
3rd Annual Lean Construction Conference Alb, NM	1	1				×								
33rd Annual Paving & Transportation Conference Alb, NM	4	4					×							
TRB Presentation to CM Committee Washington DC	1						×							
WASHTO Committee Presentation	1							×						
Pilot Training Workshop KY	3								×					
Training Workshop Albuquerque, NM	7									×				
TRB Session	1										×			
IDEA Proposal												×		
Publications in Transportation Journals		2 - 3										×	×	

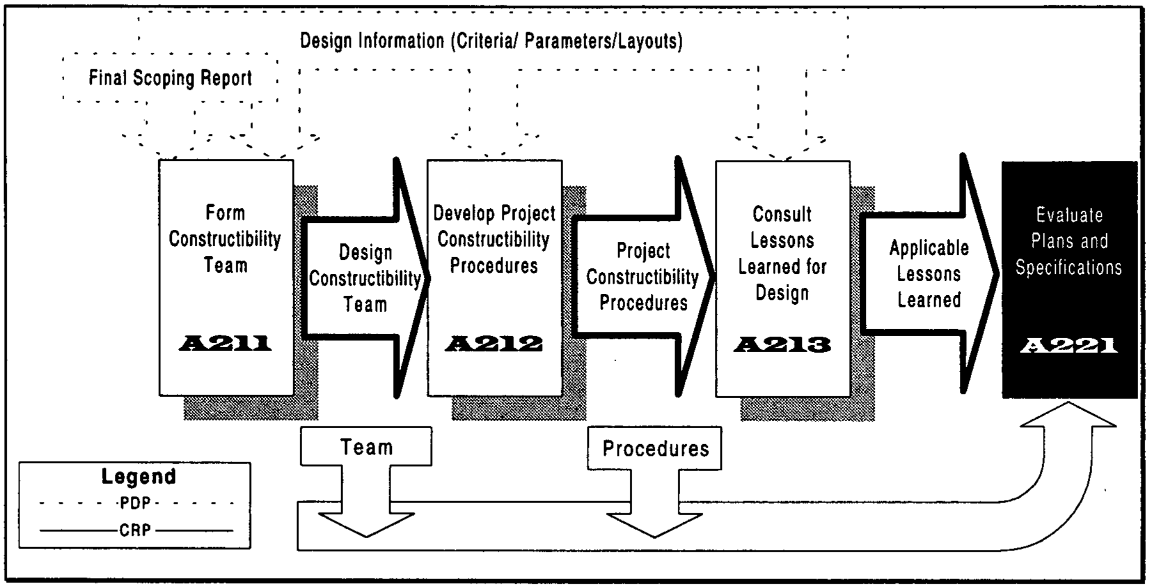

Figure 39. Implementation of the CRP during the design phase.

sourced to a construction management firm or supplied from within the agency.

Contract language may be required to ensure the application of the CRP during design. Additionally, clear specifications would be essential to determine the role and responsibility of the consulting organization, including the interface with the project constructibility coordinator. Partnering may be a technique that would help develop a team approach to constructibility. The agency must accept the up-front planning and cost for implementing the CRP. Documentation of constructibility improvements should occur as the remaining constructibility functions of the CRP are applied during project design. This will help track results of the constructibility effort and provide input for future projects.

3. In-house planning and design for a standard project—A third approach to implementation is to start a standard project using the full CRP. The CRP begins during planning and continues through the end of construction. Planning and design should be performed in house to obtain the full learning benefits of using the CRP. The project selected should be a standard project, similar to the Buffalo Gap Intersection described in the workbook, with minimum discontinuity between the planning and design phases. The process need not be highly formal and would require only a few key participants. All recommended constructibility functions outlined in the workbook should be performed. The CRP itself should be tracked to assess overall results. Documentation of constructibility improvements should be compiled during each project phase. As experiences are gained with constructibility, the CRP can then be applied over time to more complex projects.

In each pilot project, benefit/benefit data should be tracked through the CRP. Results should be reported to senior management to confirm the success of the CRP. This should promote further application of the CRP.

Team Approach

A team approach is desirable for implementing constructibility. Due to its multidisciplinary nature, such a team can organize the appropriate expertise to address constructibility issues. Further, the collective experience of this team can often provide constructibility knowledge when this knowledge is not readily available through a single source. As shown in Table 13, a constructibility team can consist of core and ad hoc members. Core team members should include professionals from planning, design, and construction within the agency. Ad hoc members are specialists used as needed depending on project complexity and characteristics.

A project constructibility team could be one person with ad hoc assistance or a large group of experts representing several disciplines. The effort necessary on the part of the core team changes as the project moves from planning to the design phase and then construction. Ad hoc assistance can be sought as needed throughout the project duration. To ensure constructibility implementation, care should be taken to ensure continuity of the team as projects move through different phases. Formalization of the CRP would ensure such continuity.

Agency Strategies

Although implementation of the CRP can be initiated on small pilot projects at the project level, to sustain CRP

TABLE 13 Design constructibility team composition

Constructibility Team	Possible Members
Core Team Members	o Design team representative o Construction experts o Planning and owner agency representatives
Ad Hoc Members	o Structural consultants o Project management experts o Safety and environmental experts o Value engineering and budget experts o Right-of-way and property experts o Traffic, maintenance, and level-of-service experts o Specialized engineers and consultants o Contractor agency representatives (AGC, ARTBA) o Construction Manager

implementation over time an agency infrastructure is required. Three major elements are suggested in developing an agency-level infrastructure for a constructibility program, as illustrated in Figure 40. They are

- development of a learning organization culture,
- commitment to implementing constructibility, and
- establishment of a formal constructibility program.

Organizing for Constructibility

Initially, focusing on organization culture, an environment of commitment should be created to ensure that a constructibility program will not only be effective, but even survive. Change will be required and must be recognized and managed.

Next, commitment can be sustained as key agency personnel become familiar with the objectives, methods, and concepts of constructibility. Early efforts should be focused on training senior management to secure their active support and involvement in program implementation. Then, an assessment of in-house constructibility capabilities and practices should be conducted. This should determine current practice within a particular agency, identify barriers to constructibility, and confirm need for improvement. Barriers must be removed to achieve successful implementation of constructibility. Commitment to implementation of constructibility would not be complete without the development of an implementation policy. Such a policy gives prominence to an agency constructibility program, ensures a high level of commitment, and defines the level and extent of program efforts.

Finally, establishing an agency constructibility program requires a constructibility sponsor or champion, a recognized agency leader with a high level of authority and influence. This person should be dedicated to the cause of constructibility. He or she should possess proper technical and managerial experience, as well as time to devote to the position. The sponsor or champion must be empowered with the full support of agency executive management.

Besides the constructibility sponsor or champion as shown in Figure 41, two other positions are recommended for an agency-level organization: (1) constructibility program manager; and (2) database custodian. Among the responsibilities of the constructibility program manager are

- coordinating day-to-day agency-wide constructibility efforts,
- supervising project constructibility coordinators, and
- tracking agency constructibility program goals.

The database custodian is responsible for

- documentation,
- tracking, and
- distribution of constructibility ideas and experiences.

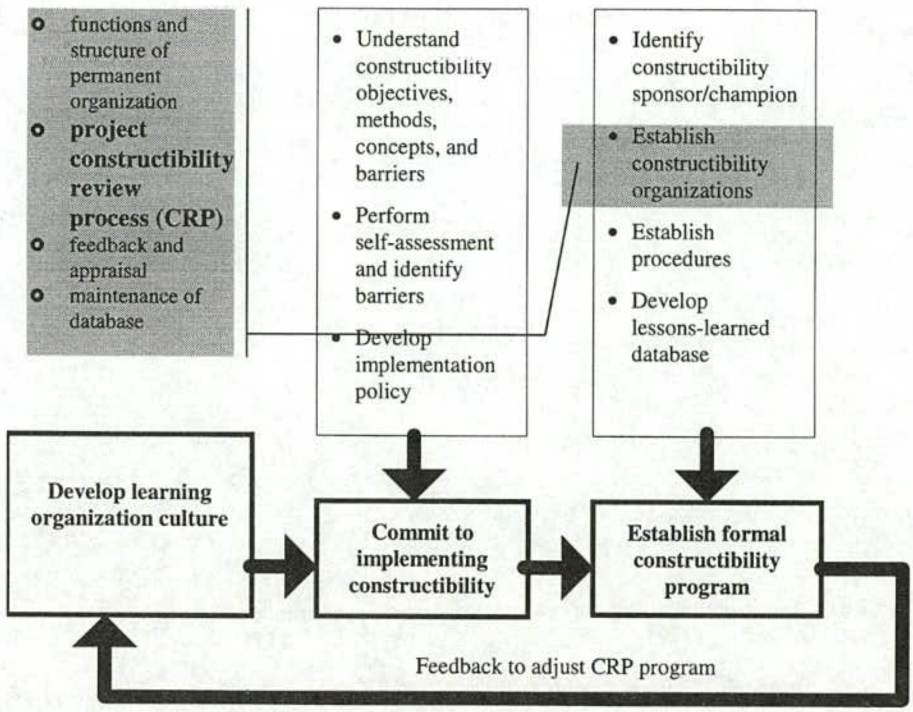

Figure 40. Elements of a constructibility program.

Procedures for agency constructibility programs should be minimal. Procedures should include the structure of the agency constructibility organization, definition of roles and responsibilities of this organization, a project CRP, a feedback process for constructibility ideas and experiences, and the maintenance of the agency lessons-learned database. This database becomes one of many sources for a project to access lessons learned, as denoted in Figure 42. Development of a lessons-learned database is a substantial effort and, therefore, will be discussed in some detail next.

Lessons-Learned Implementation Strategies

The CRP is based on accessing construction knowledge and experience. This resource is primarily obtained through the experience of individuals. Another source may be those experiences captured on previous projects. Unfortunately, these lessons learned are rarely documented for future use. Application of lessons learned in conjunction with constructibility analysis is a key concept leading to effective implementation. Lessons learned represent an organized col-

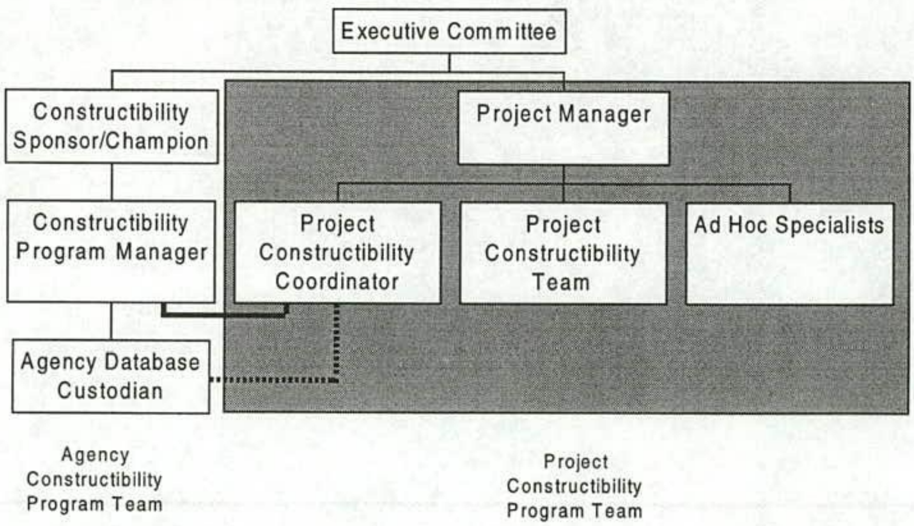

Figure 41. Constructibility organization structure.

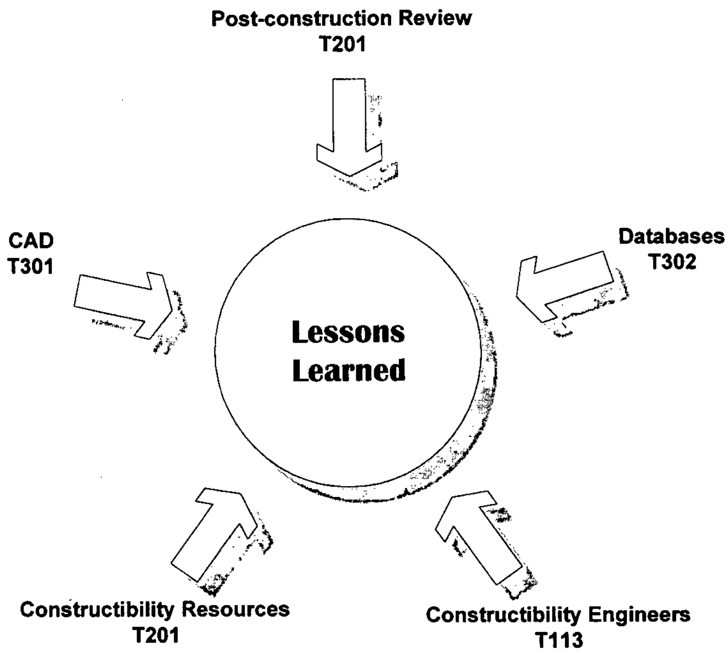

Figure 42. Sources of lessons learned.

lection of design and construction experiences, both successful and unsuccessful, gained from past projects.

A mechanism for collecting, storing, and retrieving lessons learned must be implemented by STAs to gain the full benefits from formalizing the CRP. The issue of design and construction knowledge and experience is the premise for developing a lessons-learned database. The process of building such a database will take time and effort. Senior agency management must be committed to establishing this database.

The CRP is structured to document constructibility improvements as they are identified. Functions are also included to capture knowledge and experience during construction. It is possible to start collecting constructibility improvements at various times in design, such as during 30, 60 and 90 percent design review sessions. The ultimate goal, however, should be continuous collection of constructibility improvements and ideas that could be used on future projects as depicted in Figure 43. With time, an agency can

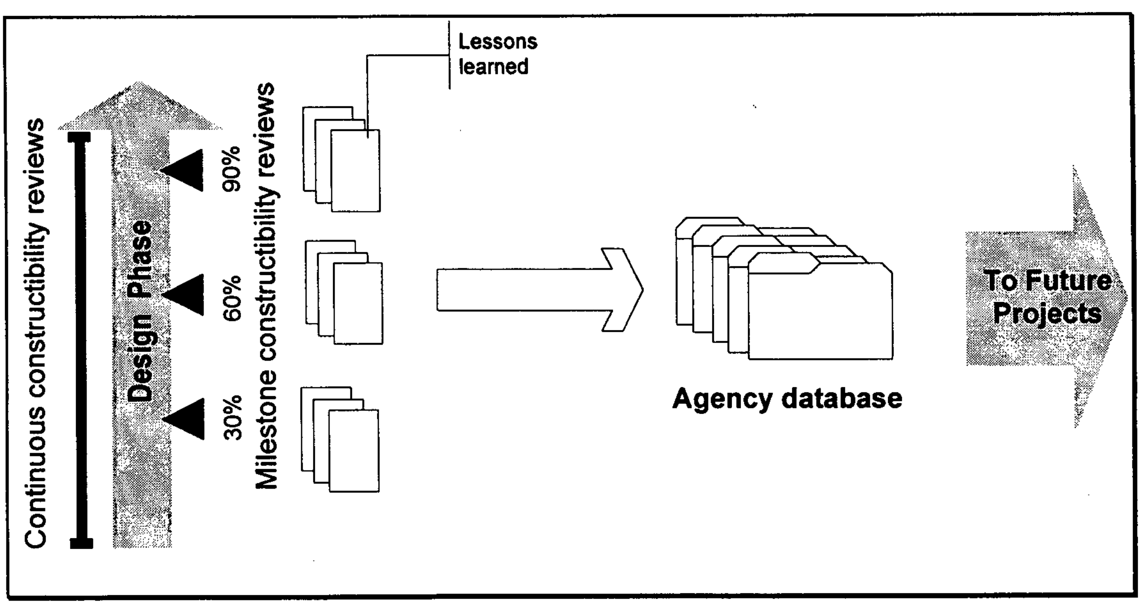

Figure 43. Capturing lessons learned.

build, expand, and use the lessons learned generated from the CRP, provided an agency-level database structure is available.

One readily available source of lessons learned is a multimedia CD-ROM constructibility system developed at Purdue University for the Indiana DOT (*11*). This system incorporates a database of lessons learned. These lessons learned are accessed through different types of multimedia applications such as text, drawings, and videos. This system provides an easy way to access lessons learned during the design phase. It also can be expanded for use during the planning phase. This system is described in more detail in Appendix B.I of the CRP workbook (*1*).

At the agency level, guidelines should be developed for establishing an initial lessons-learned database that does not first rely on results of project CRPs. Figure 41 illustrates a proposed set of guidelines being developed by the CII research team "Modeling the Lessons Learned Process" (*39*). Each column in this model represents a step in the lessons-learned process, depending on the area of responsibility. These steps and their descriptions are as follows:

1. *Coordination*—This is usually the role of an individual who is responsible for collecting, acknowledging, screening, categorizing, and prioritizing the knowledge.
2. *Contribution of information*—This could be started by actually soliciting lessons learned through a survey both within (construction staff, etc.) and outside (contractors, etc.) the agency. Each source would provide lessons learned on the survey from their experience that could then be analyzed and catalogued into a database for future expansion and implementation.
3. *Analysis of information*—Lessons learned need to be analyzed by either an individual or a team to determine whether they add value and the magnitude of this value added.
4. *Plan of action*—An analysis team will analyze the lesson learned to determine if improvements are required. If so, an action team can be formed to perform this function.
5. *Implementation of knowledge*—This process includes incorporating lessons learned into the database. It also involves looking at any work processes that may be impacted by the lesson, necessitating the revision of policies and/or procedures. Finally, this step involves agency training and post-implementation analysis.

These guidelines are offered as one source to help an agency design a lessons-learned system. An attempt to develop this system must be well planned and then managed carefully.

Pilot Project Proposal

As part of the knowledge transfer process, three pilot projects from at least two STAs should be selected for implementing a formal CRP. These projects would then be benchmarked based on some criteria (e.g., benefit/cost, percent change orders, and customer satisfaction) and compared with other similar projects that do not have a formal CRP. A constructibility team approach is recommended for this implementation process using a different mix of participants from within and outside of the agency. This process will start small with the intention of building later.

Agency-level issues that will be addressed on these three pilot projects could involve alternate contracting strategies (construction management approach, design/build approach, or contracting for constructibility review services) or using professional associations for outside constructibility input. Other agency-level issues that would also be addressed would include ways to promote an agency culture for change and organizational learning. Finally, CRP implementation barriers and barrier breakers would be identified and solutions developed.

Another agency-level issue that would be addressed on these pilot projects would be developing a systematic lessons-learned process. Guidelines, such as those shown in Figure 44, could be developed and tested on a limited basis. Finally, the integration of possibly a future tool, such as computer simulation or virtual reality, for constructibility analysis would also be proposed as part of the implementation strategy on at least one of the three pilot projects.

Resources

Resources required to initially implement a CRP within an agency do not have to be extensive. A range of options is available, depending on agency resource levels in terms of time, money, people, and computing hardware/software capabilities. Because of the diversity in available resources, at both the agency and project levels, individual agencies are in a better position to estimate the time and costs associated with resource utilization that best fits their particular agency or the project application at the time of consideration. Types and level of resources needed are suggested in the following section.

Agency-Level Resources

Agency-level resources suggested to implement a CRP can be divided into people and computing hardware/software. As a minimum, two people are required: a constructibility program coordinator and a database custodian. Existing personnel may be used either full time or part time. Also, involvement of a part-time senior policy maker as the champion or sponsor is required. An additional person may also be needed (full or part time) for the development of future tools. Issues related to hardware/software could vary over a wide range, based on sophistication of the computer tool used. For example, full implementation of a lessons-

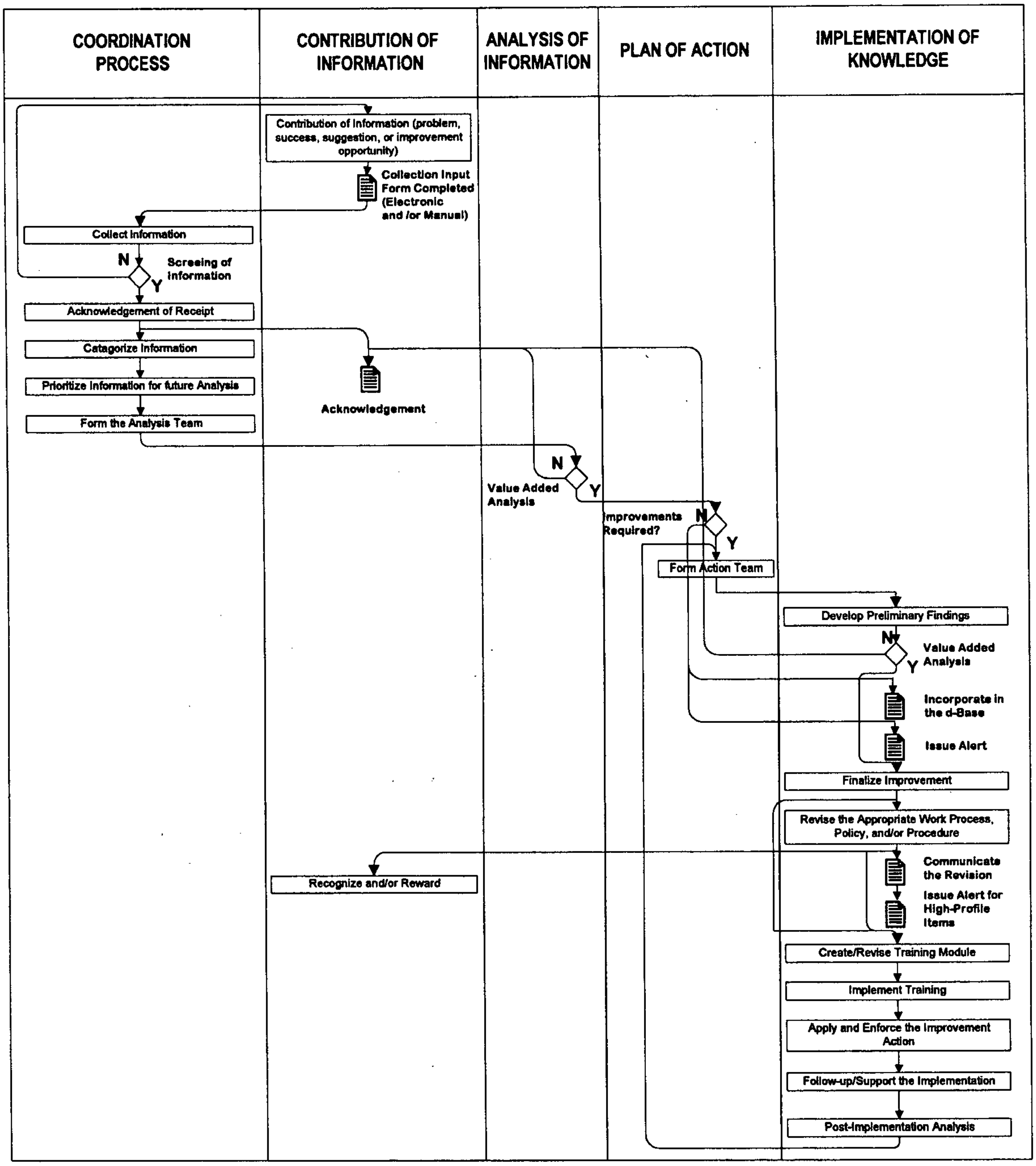

Figure 44. Lessons-learned process model (39).

learned database would require more computerization capabilities. Issues, such as degree of networking, to support a lessons-learned database would also cause variation in computing resource utilization.

Project-Level Resources

Project-level resources would also vary, as a function of the size and complexity of the project. Most projects could use existing personnel on a part-time basis as members of the constructibility team. On very large projects, a constructibility engineer may be added either part or full time. If design is performed in house, but expertise is not available, then outside constructibility resources may be required. If design is outsourced, an additional resource may be required for partnering, or an outside consultant may be required to specify constructibility contract language. This outside consultant could be either a construction management firm or an individual consultant. If team building is used on a project, additional outside facilitators might be required. Also, a project person is necessary (either part or full time), to track constructibility improvements for future lessons learned.

Research-Level Resources

Regarding research-level resources, the cost in time, money, and resources to conduct the pilot project proposal described in the previous section is estimated as follows:

Approximately 2- to 3-Year Duration

2 part-time academics for 2 yrs	$50,000 to $70,000
2 part-time graduate students for 2 yrs	$60,000 to $90,000
Supplies/materials	$15,000 to $20,000
Travel	$15,000 to $20,000
Indirect	$70,000 to $90,000
Total	**$210,000 to $290,000**

These monetary resources could be obtained through direct solicitation from TRB state representatives or from AASHTO research advisory committee representatives. They could also be obtained from a written proposal to the NCHRP IDEA program.

CHAPTER 9

CONCLUSIONS AND FUTURE RESEARCH

This final chapter summarizes key conclusions with respect to an assessment of the CRP and its potential for implementation at both the agency and project levels. Future research opportunities are highlighted.

CONCLUSIONS

Conclusions focus on five areas: (1) general; (2) critical success factors; (3) pilot projects; (4) full-scale implementation; and (5) no more excuses. Each of these areas will be discussed individually.

General

As indicated through current practice assessments, constructibility is performed informally by most STAs. Of those STAs that have attempted to formalize constructibility, few have identified a structured process with key functions that lead project personnel through implementation. Most constructibility analyses, whether informal or formal, are driven by project milestones during design, when "reviews" are conducted. They are also conducted late in design, which minimizes benefit/cost. Constructibility is considered part of these design reviews and often is not afforded the attention required to maximize benefits. Minimum constructibility analysis occurs during the project planning stage.

At the agency level, there is a distinct lack of any support organizational structure for implementing constructibility. Very few agencies have a single person responsible for constructibility. Few agencies use outside expertise to obtain constructibility input, or contract language to encourage consultants to perform formal constructibility reviews, or alternate contracting strategies that might promote constructibility reviews. The techniques of value engineering (VE) and partnering are just being used, but only during construction and not on all projects. Also, most agencies do not track constructibility lessons learned or use computing technology to aid in constructibility analysis.

Implementation is impeded by certain critical issues. In project execution, major issues cited are a lack of feedback to designers, timely and knowledgeable input of construction experts, communication between project participants, and adequately coordinated plans and specifications. Key issues relevant to project planning and technical design documents include clarity of plans and specifications, traffic control, construction phasing and sequencing, environmental considerations, and safety. Finally, project resources are limited and of particular concern are issues related to adequate time for reviews, availability of funds and personnel for reviews, and lack of the right experience and knowledge.

To address these critical issues, potential paradigm shifts have been identified at both the project and agency levels. These paradigm shifts are summarized as follows:

Project-Level Paradigms

- Formalize project constructibility processes to include planning, design, and construction.
- Implement use of constructibility review tools.
- Use team approach.
- Enhance plans, specifications, and contract documents for constructibility.
- Provide feedback to designers on construction performance of design.
- Collect feedback from maintenance and operations personnel.

Agency-Level Paradigms

- Establish an agency constructibility policy.
- Recognize favorable benefit/cost ratio.
- Allow for alternate contracting strategies.
- Use a constructibility consultant/engineer coordinator.
- Develop and implement a constructibility lessons-learned database.

The CRP addresses the project-level paradigms by formalizing the process beginning with planning, then design, and through construction. A set of constructibility functions is defined with steps and actions. Review tools are introduced to assist in carrying out steps and actions. A team approach is recommended that can provide for the right expertise within the constraints of time, money, and people. Mechanisms to obtain input from operations and maintenance personnel and feedback to designers are incorporated into the process. The end result should be enhanced plans and specifications for constructibility leading to increased ease and efficiency of construction, with fewer changes.

The CRP includes attributes that will require some agency-level paradigm shifts to sustain the process over time. An agency policy is required that provides for a champion, organization structure, and evidence of commitment to constructibility. Alternate contracting strategies can be incorporated into the CRP to facilitate timely input of construction knowledge and expertise. Agencies can use a constructibility engineer coordinator to aid in project constructibility reviews and to promote use of the CRP on different project types. Agencies can conduct reviews earlier in the PDP and incorporate VE and partnering sooner. Finally, a constructibility lessons-learned database can help make construction knowledge and expertise available to future projects. Use of lessons learned is a key feature of the CRP.

Critical Success Factors

Any process improvement initiative, such as the CRP, will not be applied unless certain critical success factors are achieved. At the agency level, these success factors include the following:

- Senior agency management must be informed. They must understand why constructibility is important, what the benefits are, and how constructibility can be implemented.
- Senior agency management must take a position in support of constructibility. This is reflected in a clear commitment to support a CRP throughout the agency.
- Senior agency management must commit the necessary resources—time, people, money, and computer software and hardware. These resources are required at both the agency and project levels.

These factors are addressed through the CRP workbook and this final report. At the project level, the primary critical success factors are:

- Project participants must be educated. This includes a general understanding of why constructibility is important, how a CRP can improve project performance, and when during a project the CRP should be implemented.
- Project participants must be trained. They must obtain an in-depth understanding of how the CRP works. This would include the use of tools in support of the steps and actions required to implement constructibility during each phase of the project development process.

Many functional disciplines must be involved in this education and training effort. Constructibility will work best when a team approach is used with diverse representation and expertise.

Pilot Projects

Pilot projects are the most important vehicle for an agency to begin to formalize a CRP. However, pilot projects must be chosen with care. Some criteria are needed for

- **Selection of projects.** Small projects that require minimal constructibility efforts can be used to apply the CRP from planning, through design and construction. Planning and design should be performed with in-house resources. Moderately complex projects that require an increased level of constructibility analysis can be used to apply the CRP during design. Using in-house resources may be a better approach than outsourcing the design until some expertise is gained in application of the CRP.
- **Execution of projects.** If the CRP is applied through all phases, project execution should be as continuous as possible to maintain continuity of the constructibility team. If the CRP is applied only during design, some follow up should occur during construction to monitor how the design performs.
- **Feedback mechanism on projects.** If the CRP is applied through all phases, then the CRP will provide feedback if all functions are performed as specified.

  If the CRP is applied only during design, then a feedback mechanism must be intentionally added to the design process to evaluate the CRP. This could be accomplished through documenting constructibility improvements incorporated into the design and the benefit/cost of these improvements. Some analysis of the impact of constructibility improvements on the ease and efficiency of construction should be made.
- **Training and education.** Project participants should be educated and trained in the use of the CRP prior to implementation. Agency senior management should fully support pilot projects. Finally, as the CRP is used, application of it in all project phases should be initiated.

Full-Scale Implementation

As pilot projects demonstrate the success of the CRP, an agency should move to full-scale implementation. This could occur simultaneously with project-level implementation. Full-scale implementation can be accomplished through the following:

- **Training.** A broad agency-wide training effort would be required. This training should permeate all levels within an agency. It should cover agency infrastructure issues such program objectives, policies, commitment of senior management, and barriers to implementation. Project-level training would then focus on the CRP and the mechanisms involved in using the process.

- **Process reengineering.** Many STAs lack documented project development processes. In order to effectively implement constructibility, the project development process (PDP) must first be documented. Then, the CRP can be integrated into the PDP. This may, however, require reengineering of the PDP to better adapt the CRP for timely application within the context of the PDP. Since the CRP is presented in guidelines, the specific guidelines may be changed to more closely align with agency practices and culture.
- **Process improvement.** As results from the CRP become apparent, ways to improve this process will certainly be identified. The CRP itself has a function that helps in identifying process improvements. They must be acted upon. Improvement could include automated lessons learned or use of selected future tools.
- **Future tools.** As part of process improvement the T4000 tools should be reviewed by STAs to see how they can be integrated into the more developed CRP for continuous improvement.
- **Agency culture.** Implementing a new and formalized constructibility program will necessitate change within the organization. Barriers caused by ingrained paradigms, such as tradition and inflexible attitudes, will have to change. Procedural barriers resulting from established practices deemed "set in stone" will have to be removed. Awareness barriers caused by a lack of understanding of the goals, concepts, methods, and benefits of constructibility will have to be overcome by training and education. Finally, incentive barriers arising from the absence of motivation for constructibility implementation will have to addressed.

Full-scale implementation will take time as each of these issues is considered.

No More Excuses

STAs now have have a formal CRP to implement constructibility. This process leads project personnel through the application of constructibility at various stages of the project development process. It includes guidelines that specify steps and actions with tools to help implement the details of the work process. Suggested approaches to establish an agency infrastructure for a constructibility program are also included. Time and effort will be required to implement the CRP. With these tools and information, reasons for not implementing constructibility are difficult to substantiate. Benefit/cost data are available that indicate a $25 project savings for every dollar spent on constructibility analysis. STAs no longer have any excuses.

FUTURE RESEARCH

Future research would support implementation and provide a vehicle for demonstrating the success of the CRP. Areas discussed include case studies, application of advanced computing technology, and continuous improvement initiatives.

Case Studies

Case studies can be an effective research mechanism for rigorously applying the process. A number of different projects is recommended in the implementation plan (Chapter 8). These projects would attempt to maximize the application of the CRP by using the process under various conditions. Results of case studies would be documented and serve at least two purposes. First and foremost, success stories are frequently the best vehicle to encourage greater application of a formal process. Second, modifications and improvements can be made to the CRP to ensure the process meets the needs of STAs.

Technology

Computing technology has the potential to automate many components of the CRP. However, as a result of the current practice assessment, very few computing tools have been incorporated into the implementation guidelines of the workbook. Four tools are included in this category:

- CAD/GCCA,
- Databases,
- Hypermedia/Multimedia/CD-ROM/Hypertext, and
- EDI/Bar Coding/Pen-Based Technology.

These four computing tools may be areas where initial research efforts should be focused. Most STAs have the technology to implement them. General research is being conducted in all four areas. Additional research might help facilitate how each tool can be integrated into the CRP to more fully automate certain constructibility functions. A prime target here would be to develop STA worksites with access to one another's databases to share constructibility lessons-learned databases. These databases can include multimedia and GCCA animation.

Future tools is another area in which research efforts are warranted. Since most future tools are considered useful for a mature CRP, the timing of this research is not as critical. However, many future tools have the potential to substantially enhance the CRP. Research in these areas will take more time to complete. Starting research initiatives now may provide an advanced tool when the CRP is more fully developed over time. Four future tools that have potential for implementation into a mature CRP are (1) Alternate contracting, (2) Financial modeling, (3) Case-based reasoning/expert systems, and (4) Simulation.

Alternate contracting schemes, such as fast tracking with design/build should be furthered with widespread implementation of the CRP. Financial modeling techniques to study schedule impacts on businesses could be developed and integrated into the CRP. A case-based reasoning system could be developed to match current STA projects with past projects of a similar nature so that constructibility lessons learned could be transferred automatically among projects.

Expert systems that have already been developed by STAs (see Chapter 2) can be modified to be incorporated into the CRP. Finally, simulation models could be developed to study phasing/staging and sequencing of construction activities to enhance the scheduling of traffic control.

Continuous Improvement

Mechanisms should be studied that provide for continuous improvement of the CRP. As the CRP is implemented by STAs, some possible approaches might include the use of conferences and symposiums to study applications of actual users. AASHTO might sponsor workshops to examine the impact of the CRP and identify specific improvement initiatives STAs have tried to enhance the process. Lessons learned specifically related to the CRP might serve as another source for improvement ideas. These ideas can be collected through the CRP because the CRP provides a constructibility function to perform this type of evaluation.

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APPENDIXES A AND B

UNPUBLISHED MATERIAL

Appendixes A and B as submitted by the research agency are not published herein. Copies are available for loan on request to NCHRP, 2101 Constitution Ave., N.W., Washington, D.C. 20418.

Appendix A	Survey Questionnaires
Appendix B	IDEF0 Models Used for Developing Preliminary CRP Framework

APPENDIX C

ANALYSIS OF BENEFIT/COST ON SELECTED ADOT PROJECTS

INTRODUCTION

In 1992, the Arizona Department of Transportation (ADOT) established a Constructibility Engineer position. The person in this position had an extensive background in both transportation design and construction. Plans and specifications were reviewed by this person to determine possible improvements from a constructibility perspective. Data from these reviews indicated that constructibility efforts applied to transportation projects offer very attractive benefits. In a set of six projects selected from 35 reviewed for constructibility (Table C.1 shows a complete list), the savings achieved as a result of constructibility improvements amounted to 1.7 percent of the total construction cost of the six projects (about $68 million). This percent savings translated to $1.2 million. The cost of the review effort was such that the benefit to cost ratio was 25 to 1. Thus, for every dollar spent reviewing these ADOT projects for constructibility, $25 was returned in project savings.

The ADOT Constructibility Engineer provided the actual constructibility analysis on the following selected six projects. Benefit/cost was developed for each project to illustrate the potential project savings through analytical focused constructibility reviews. Actual construction bid costs were used, because the design costs could not be identified.

Project RS-324 (4): Historical Site Turnout-Slide

This project focused on a slide repair. Three slides had occurred on SR 260 MP 234 between Payson and Strawberry. The approximate amount of material that had to be removed from the three areas was 59,000 cubic yards. About 35 percent of the material could be reused for embankment. The balance was deposited at a nearby USFS pit. A total of 73,000 cubic yards of embankment was needed for replacement. The fill was designed for a shot rock embankment. Subtracting the usable existing material would then require 52,000 cubic yards of additional material from a proposed embankment source, Clover Creek. Clover Creek was a cut-widening project under construction at the same time. The proposed access was too steep, and there were no provisions for a truck turnaround. The constructibility suggestions were to flatten access to no more than 15 percent grade and to design a continuous haul road through slides numbers 2 and 3.

Project STP-073-1(12)P: Clover Creek Cut Widening

Clover Creek, as has already been pointed out, was a cut-widening project. This cut, in limestone, was required to reduce an icing problem for winter traffic on SR 87 MP 278.5. Existing slopes were almost vertical and close to the roadway shoulder. There were problems with low swell (10 percent) with the limestone material and a long haul (24 mi) to the Historical Site Turnaround. The constructibility suggestions were (1) adjust the swell to 15 percent and reduce the cut volume and (2) screen existing slide material at the Historical Site Turnaround to reduce haul distance and dispose the unusable material at closer location.

Combined construction cost	$1,963,000
Combined estimate savings	$159,000

Project F-073-10-510 Intersection Improvement: East Verde Road

This project, located 7 mi north of Payson on SR 87 MP 257.6, involved widening of an existing turnout area as a safety improvement. A subdivision located to the west of the highway had grown substantially. Traffic exiting onto SR 87 had poor sight distance and access, both in and out. The turnout is located at the bottom of a sag vertical curve. Traffic approaching from the south was proceeding downhill on a −6 percent grade. A horizontal curve, approximately 500 LF south of the intersection, offered poor sight distance. Most of the vehicles entering the subdivision would make a left-hand turn from the south to the west. A vehicle in this position could easily be rear ended from northbound traffic that had no maneuvering room. There was an existing bridge located 300 LF to the north of the intersection. The bridge restricted the length of widening between the intersection and the bridge to the north. The constructibility solution was to eliminate fill slope by shifting alignment 8 ft to the east. This increased roadway excavation by 15,000 ft^3.

Construction cost	$778,535
Estimated savings	$95,000

Project NH-10-3 (317): Superstition T.I. Unit II Construction Sequencing

This project consisted of the construction of two overpasses at a busy interchange. Construction was split into two

TABLE C.1 Projects/Reports Reviewed by the ADOT Constructibility Engineer

Project RS-324(4) Historical Site Turnout, SR 260 MP 234
Slide repair job with difficult access in USFS.

Project STP-073-1(12)P Clover Creek, SR 87 MP 278.5
Limestone cut widening in USFS, rock to be used on RS-324(4).

Project F-073-1-510 Intersect. Impvmt., SR 87 MP 257.6
Intersection widening for East Verde Rd. to subdivision.

Project NH-10-3(317) Superstition T.I. Unit II
Review the construction phasing to determine its constructibility.

RAM 600-1-536 Pima, Red Mt. T.I.-Phase II, Thomas to McKellips
Review 60% plans for Gr, Dr, Pvmt.

Project STP-029-1(8), Cordes Jct-Prescott Hwy. (SR 69), Humbolt-Jct SR 169
Review 95% plans for phasing—Gr, Dr, Pvmt.

HDP-920-5(001) Sky Harbor Expressway (SR153)
University Dr.-Sky Harbor Blvd.—60% Submittal, 95% Submittal.

Final Materials Memo, Nogales-Tucson Hwy (I-19), Arivaca-Green Valley
Review typical milling/paving section for constructibility.

PLH-038-1(19)P State-Creek Section (SR 188)
Reviewed 60% plans—Construction Sequencing Plan.
Determine durations from 95% plans.

NH-40-3(70) I-17/I-40 Traffic Interchange, Flagstaff
Constructibility for Ramp E-N Underscrossing.

RAM-600-1-534 Pima/Indian School Rd.
Reviewed 95% plans for construction sequencing.

STP-366 (21)P Oak Creek Canyon, Rockfall Containment (MP 379 US 89A)
Made site review for access problem for E.A.

RAM-600-2-320 I-10/Loop 202 Ramp to Thomas Rd. SR 51
30% Plans review on new median PCCP paving/concrete barrier.
95% Plans submittal.

STP-029-1(17)P Big Bug Br #4-Poland Jct SR 69
60% Plans review on construction phasing.

STP-074-1(1) Ortega Lake-St. Johns, Blackridge Section SR 61 (MP 379) 60% plans.

SR 188 MP 245 Slide project. Slope layback and widening.

SR 88 MP 243/8 Slide project. Slope clean-up and rock nailing.

STP 053-1(29) McDowell Rd.—Shea Blvd. (SR 87)
Review 60% plans for construction phasing regarding drainage.

IM-17-2(116) Sedona T.I.-County Line (N.B. I-17)
Review 60% plans—project advertised with construction industry for feedback on constructibility and bidability.

STP-044-1(16)P A 1 Lake-Jct SR 273 (on SR 260)
Review 30% plans—phasing for reconstruction section.

F-016-1-529 Mule Pass Climbing Lane (SR 80)
60% Plans Review and field trip to inspect granite rock cuts.

F-053-2-513 Diamond Point Road Widening (SR 260)
Estimated work schedule for Traffic Engr.

F-038-1-508 Vineyard Canyon—Ash Creek (SR 188)
Estimate for Rip Rap Item prior to bid.

S-366-531 Jerome Retaining Wall (US 89A)
Field review based on 30% plans.
Review 95% retaining wall structure sheets.

Review of proposed Section 203 Earthwork specification

Segment E SR 87 30% plans.
Construction Access Screwtail Bridge.

Embankment curb construction under guard rail ribbon

S-559-508 Page Bypass (SR 98)
US 89 to Coppermine Rd. 60% plans estimate for major bid items.

Blasting/Traffic Control Spec (60%)
SR 87, Segments A-F.

Cost Estimate for Emergency Job.
I-10 Chandler Blvd—Baseline Rd.

RAM-600-0-518 I-17/101 T.I., West Half of T.I,
95% plans. Determine construction schedule duration.

RAM-600-2-514 SR 51 Squaw Peak, Shea Blvd. to Thunderbird Rd.
Preliminary plans (15%) Develop construction schedule.

STP-002-4(8)P Columbus Blvd., Tucson
Review intersection improvement project.

101 L 14A 55r US 60/Loop 101 T.I. (Price/Superstition T.I.)
Review partial plans for construction sequencing and schedule.

Becker Butte Slope Stabilization, MP 296.6 US 60
Comments on draft scope.

stages, each with a sequence of activities. There was a problem with the proposed sequencing as material would not be available for Stage 2 embankment construction. The constructibility solution consisted of re-phasing the project to provide the material to meet the schedule.

Construction cost	$24,911,000
Estimated savings	$375,000

Project STP-029-1(8): Humbolt-Jct SR 169

This project consisted of the construction of a new 12′ × 12′ CBC. This required staged construction for present and future alignments and provision of temporary drainage during construction. The constructibility suggestions were to eliminate both the temporary 72″ × 68″ CMP and the median catch basin and to construct a new concrete box culvert in phases with protection.

Construction cost	$3,860,000
Estimate savings	$19,200

Project RAM-600-0-518: I-17/101 T.I.

This project involved the construction of an overpass at a busy interchange. There were problems with phasing and traffic detour. The constructibility solution was to change the temporary I-17 detour from the west to the east side, thereby eliminating staged construction of fly-over structures.

Construction cost	$37,057,000
Estimated savings	$487,000

Project ER-038-1(29): Roosevelt Lake Emergency Slide Repair, SR 188 MP 244.05

This project involved drilling and shooting approximately 42,000 cy of rock to flatten the cut slope in a slide area on the right side (south) of SR 188. There was a problem with constructing an access road to the top of the cut for slope layback. The constructibility solution was to eliminate the proposed access road, which involved blasting and remediation. Access from the top of the ridge via an existing road system was used instead; thus no construction was required.

Construction cost	$847,000
Estimated savings	$35,000

Benefit/Cost Summary

The benefit/cost ratio shown in Table C.2 is based on a constructibility expenditure of $200 per hour. This rate would cover the compensation for the Constructibility Engineer, the additional overhead needed to support constructibility at the agency level, and the cost of drawing revisions. The benefit of constructibility as shown here on six projects is consistent with other industry applications.

TABLE C.2 Benefit/Cost Summary on Constructibility for Six Selected ADOT Projects

Project	Construction Cost	Estimated Savings	Estimated Hours
Historical Site/Clover Creek	1,963,000	159,000	48
East Verde Road Intersection	778,535	95,000	40
Superstition T.I. Unit II	24,911,000	375,000	40
Humbolt-Jct SR 169	3,860,000	19,200	8
I-17/101 T.I., West Half	37,057,000	487,000	56
Roosevelt Lake E.R. Site 2	847,000	35,000	16
	$69,416,535	$1,170,200	208

Benefit / Cost = ($1,170,200) ÷ (208*hrs.* × $200/*hr.*) ≈ 25/1

APPENDIX D

GLOSSARY

As-Built Drawings. Drawings of a facility as it has been built, incorporating changes made during construction.

Agency Constructibility Checklist. A checklist is a review guide to ensure that design features are considered for specific constructibility issues during project evaluation of plans and specifications.

Agency Constructibility Program. A constructibility program at the agency level which, sponsored by a senior policy maker, would provide support in the form of procedures, policies, and resources for project-level implementation of constructibility.

Agency Constructibility Sponsor. A top-level senior policy maker whose primary role is to maintain a high level of awareness and visibility of the constructibility program. This sponsor works also as a catalyst for change by supporting pilot projects and implementation efforts at lower levels within the organization.

Agency Database Custodian. A member of the Agency Constructibility Program core team. Mainly responsible for documentation, tracking, and distribution of constructibility ideas and lessons learned.

Agency Program Manager. A member of the Agency Constructibility Program core team. Responsible for day-to-day coordination of agency-wide constructibility efforts.

Benefit/Cost Analysis. Focuses on the costs of a particular action and the comparison of these costs with the measured gain or benefit resulting from such actions.

Concept Plan Development. The second part of the planning phase, when the planning team develops rough design parameters, captured in the Final Scoping Report, to serve as guidelines for the design team to follow when preparing the detailed design.

Constructibility. Integration of construction knowledge and experience into planning, design, and construction to achieve overall project objectives in terms of cost, schedule, quality, and safety.

Constructibility Champion. See Agency Constructibility Sponsor.

Constructibility Concepts. Constructibility concepts are representative of good practices that will enable practitioners in any organization to take advantage of the lessons learned by others and apply these lessons learned in their organization and on their projects.

Constructibility Consultant. Professional constructibility expert who helps with organizing for constructibility and provides construction knowledge and expertise.

Constructibility Coordinator. Usually a member of the project team, the Constructibility Coordinator mainly facilitates coordination of constructibility programs between the agency and the project.

Constructibility Engineer. A project team member who is responsible for providing guidance on project constructibility issues. This person must have the perspective of the agency, designer, and contractor.

Constructibility Function. Breakdown of subphases of the Constructibility Review Process into distinct elements that are further defined by steps and actions and are supported by specific tools. Constructibility functions are essential for conducting formal, project-level constructibility reviews.

Constructibility Implementation Policy. A formal document that specifies constructibility purpose, goals, and objectives of the agency.

Constructibility Improvements. Improved plans and designs resulting from constructibility suggestions, ideas, or solutions relevant to concept plans and design documents.

Constructibility Meetings. Meetings of the Constructibility Team at given intervals during different project phases to perform constructibility reviews.

Constructibility Organization Structure. Infrastructure for both Agency and Project Constructibility Program Teams, supporting constructibility efforts both at agency and project levels.

Constructibility Plan. A constructibility plan describes the strategies, level of formal procedures used, mechanisms for obtaining construction expertise, and the size and makeup of the constructibility team needed to implement a project constructibility process.

Constructibility Procedures. A series of steps followed in definite order to implement a project constructibility process.

Constructibility Resources. Sources of constructibility knowledge and experiences such as district construction engineers, construction management services, value engineering firms, retired construction professionals, or local contractor associations.

Constructibility Review Process (CRP). A process, integrated with the Project Development Process (PDP) to review projects for constructibility and collect lessons learned from previous constructibility efforts.

Constructibility Review Tools. Tools used to perform constructibility functions.

Constructibility Strategy. Directives for the constructibility effort that will support achieving project objectives.

Constructibility Team. A multidisciplinary team of in-house and possibly outside experts assembled for conducting constructibility analysis and evaluation on a given project.

Contractor Agency Representative. Representatives of agencies such as Associated General Contractors (AGC), whose expertise is sought as ad hoc members to the Constructibility Team.

Contractor-Determined Schedules. Schedules determined by contractors and designed to be performable within resources available to them, thus optimizing their work schedule and satisfying the established requirements.

Critical Path Method (CPM). The Critical Path Method is the most commonly used network analysis system. This technique of defining and coordinating work by a graphical diagram shows work activities and the interdependence of activities.

Databases. A collection of various information which has been organized into related areas and structured in a manner so as to provide easy access and quick retrieval.

Electronic Data Interchange (EDI). Technology allowing multiple access communication delivered exclusively on and between computer networks.

Executive Sponsor. See Agency Constructibility Sponsor.

Idea/Lessons-Learned Log. A format for documentation of lessons learned throughout a project.

Implementation Responsibility Matrix. A graphical description of constructibility functions that are to be performed and key players responsible for performing these functions.

In-House Construction Representative. An agency construction expert, such as the District Construction Engineer, who is a member of the Constructibility Team.

Lessons Learned. Constructibility ideas and experiences, positive or negative, obtained from past projects.

Level of Complexity. Degree of project complexity as indicated by total project cost, work hour effort, type of project, urban or rural location, grade separation, and interface with other project participants.

Level of Formality. Degree that project constructibility process is documented through formal written procedures. Formality is based on level of complexity.

Milestone-Driven. Pre-specified points on the project schedule. Use to indicate when constructibility reviews are performed based on certain percentages of completion of project design or other project completion criteria.

National Quality Initiative (NQI). The NQI is a result of the "partnerships in quality," a concept formed in 1990 at a FHWA-sponsored workshop attended by representatives from state highway administrations, the construction industry, construction associations, and academia. An NQI Steering Committee was formed by AASHTO in 1991, with memberships from the FHWA and six other national industry organizations. The mission of the Steering Committee is to solidify this partnership and the commitment to quality through policy development, training, and technical support.

Operations and Maintenance Input. Feedback to project programmers/designers from operation and maintenance personnel regarding the long-term performance of similar projects which are presently in use.

Paradigm Shift. A complete rethinking of and change in existing methods and approaches to project development.

Partnering. A program through which owners and contractors focus on developing a relationship that creates a project team united by a common project mission and objectives.

Phases of CRP. The major phases of the CRP as they relate to the Project Development Process—planning, design, and construction.

Phases of PDP. The major phases of project development—planning, design, and construction.

Pilot Project. A project used for testing the CRP before proceeding to full-scale implementation.

Policy and Objective Statement. See Constructibility Implementation Policy.

Post-Construction Review. Review at the end of construction when all responsible project participants meet together to discuss the actual performance of the project.

Pre-Bid Conference. A meeting of potential bidders for a particular project prior to the submission of bids. The idea is to exchange project information between agency and contractors.

Pre-Construction Conference. A meeting between contractor and owner held after the bid is awarded. The idea is to decide on any unresolved concerns of both the owner and contractor.

Project Constructibility Agreement. An agreement formed between all personnel and organizations involved in the constructibility process to ensure complete understanding of the project constructibility objectives as well as objectives of the team, regarding communication and responsibilities.

Project Definition. Determination of the best course of action which would satisfy the perceived need of a project.

Project Development Process (PDP). Process through which a project is developed from planning, through design, to construction.

Project Study Report. A Project Study Report captures such project information as the physical description of the facility, environmental issues, ROW requirements and orientation of structures; confirms project economic viability; and identifies basic design parameters.

Scoping Report. See Project Study Report.

Subphases of CRP. Breakdown of major phases of the CRP as they relate to those of the PDP. These subphases are Project Definition and Concept Plan Development; Preliminary Design, PS&E Design, and Final Design; and Pre-Construction, Construction, and Post-Construction.

Subphases of PDP. Breakdown of major PDP phases. These subphases are Project Definition and Concept Plan Development; Preliminary Design, PS&E Design, and Final Design; and Pre-Construction, Construction, and Post-Construction

Suggestion Forms. Forms used in conjunction with some form of solicitation for suggestions, such as a constructibility meeting, to review plans and specifications and to capture possible constructibility ideas, comments or solutions.

Surrogate Construction Contractor. A contractor whose expertise is sought for constructibility reviews.

Team Building. An organizational process to project management that emphasizes the pooling of individual skills toward achieving a project's mission and objectives.

Value Engineering (VE). A process by which a project is analyzed to determine the most basic approach to achieve functional performance requirements. Once this base is determined, all improvements are analyzed on the basis of the additional cost over the base, compared with the value of the improvements.

THE TRANSPORTATION RESEARCH BOARD is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. It evolved in 1974 from the Highway Research Board, which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate the information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 400 committees, task forces, and panels composed of more than 4,000 administrators, engineers, social scientists, attorneys, educators, and others concerned with transportation; they serve without compensation. The program is supported by state transportation and highway departments, the modal administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation

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