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Transportation Research Record 1351

Contents

Foreword

The papers in this Record were presented at the January 1992 Annual Meeting of the Transportation Research Board. The Record is divided into two parts: Construction Quality (Part I) and Construction Management (Part II).

The four papers in Part I deal with *ASCE Manual of Standard Practice 73—Quality in the Constructed Project*. They should be of interest to all parties involved in civil engineering construction, including project owners and operators, design professionals, and construction organizations, as well as construction arbitrators and attorneys.

The ASCE quality manual evolved out of several serious structural failures that occurred some 10 years ago, notably the Hyatt Hotel walkways catastrophe of July 1981. After determining that a large part of the problem of structural failures is the result of a certain vagueness as to the duties, responsibilities, and practices of the various parties under the design and construction system, ASCE prepared a manual of standard practice to define and describe the way the system should work.

Five well-qualified practitioners presented a range of viewpoints on this controversial manual at the 1992 Annual Meeting. The papers in Part I represent most of the views expressed at the meeting (only the owner's viewpoint is not represented): Iffland presents a background and summary of the manual, Fox discusses the designer's viewpoint, Nash presents the contractor's perspective, and Smith covers the legal aspects.

The papers in Part II should be of interest to state and local design, materials, and construction engineers, as well as contractors and material suppliers.

The first four papers in Part II discuss the management of transportation projects with linear scheduling methods. Rowings and Rahbar present the repetitive activity scheduling process approach for linear scheduling of projects that have a few highly repetitive yet interrelated activities. They assert that the system fills a void that exists between bar charts and critical path methods. Vorster et al. argue that network analysis techniques and bar charts do not provide the planner with an adequate means of analyzing the movement of crews through time and space. They recommend the use of the linear schedules to solve the problem and present the format and methodology. Handa et al. present a positional weight method for scheduling linear construction projects. They indicate that this method is more accommodating to restrictions in labor, equipment, and materials needed for the project. Lutz and Halpin present the results of an investigation involving the use of simulation and the line of balance concept to analyze linear construction operations. They provide a case study to illustrate the concept.

Giaramita and White discuss the innovative construction management system being used in the largest reconstruction project ever undertaken at one time in Texas. Lee and Johnson investigate the feasibility of using a portable computer at the construction job site. They discuss both a pocket hand-held computer and a voice-activated, head-mounted computer. McCullouch describes a research project performed for the Indiana Department of Transportation to define and describe an automated construction field data management system to ease the paperwork burden on field construction personnel. Russell and Severson present the results of an investigation to analyze and evaluate a plan quality evaluation form that was developed by the Wisconsin Department of Transportation. Hinze et al. discuss their analysis of cost overruns on Washington State Department of Transportation construction projects. Ellis and Kumar present the final evaluation of the Florida Department of Transportation's pilot design/build program.

Harris et al. provide an overview of the requirements for the certification of welding technicians by the American Welding Society.

PART I

Construction Quality

ASCE Manual 73: Background and Summary

JEROME S. B. IFFLAND

Subsequent to the Structures Failure Conference in 1983 in Santa Barbara, California, and a 1984 ASCE workshop in Chicago, ASCE accepted the role of producing a guide to quality in the constructed project. A steering committee was selected to plan and oversee the work. The steering committee developed an outline, statement of purpose, and principal themes for the guide and then enlisted some 40 authors and 90 reviewers to do the writing. ASCE also appointed a managing editor and a technical editor for the manual project. After several preliminary drafts, a preliminary edition text was developed. Some 12,000 copies of this text, which was designated for trial use over an 18-month period, were distributed. Comments were voluminous. On the basis of the comments, a completely rewritten text was prepared and published. This text reduced both the number of pages and the number of chapters and was rewritten by the editors rather than the chapter authors to provide consistency in style and format. The final text addresses the complete facility construction process from procurement of designers through construction, operation, and maintenance. Methods of improving quality include involvement of the design professional in construction, project peer review, quality assurance and control programs, clear definition of responsibilities, and appropriate compensation.

On December 15, 1967, the Silver Bridge over the Ohio River at Point Pleasant, West Virginia, collapsed with the loss of 46 lives. Approximately 10 years later, on January 18, 1978, the Hartford Civic Central Coliseum roof collapsed while the building was empty, so no lives were lost. Three months later, the Willow Island, West Virginia, reinforced concrete cooling tower collapsed during construction, which resulted in the death of 51 persons. On March 27, 1981, there was a failure of the Harbour Cay Condominium in Cocoa Beach, Florida, resulting in 11 fatalities and 23 injuries. The most spectacular failure in recent times was the collapse of the suspended walkways of the Hyatt Regency Hotel in Kansas City, Missouri, on July 17, 1981. This failure resulted in the death of 114 persons and the injury of almost 200. On April 15, 1982, Ramp C of the Riley Road Interchange in East Chicago, Indiana, failed during construction, resulting in 13 deaths. Finally, just before the decision of the ASCE to develop a quality manual, a span of the Mianus River Bridge, located in Greenwich, Connecticut, collapsed on June 28, 1983, with three killed and three injured.

These failures illustrate design mistakes, construction errors, and lack of adequate inspection and maintenance programs. Whereas a structural failure is an extremely rare event, when they happen the resulting publicity gives our design and construction industry a black eye. In the public's mind, something is wrong. Henry Petroski, in his entertaining and discerning book *To Engineer Is Human* (*1*), has satisfactorily addressed this problem using many of these same examples and has pointed the way to the solution. As stated in the book, technology is not running amok; engineered structures have been failing for centuries. The first recorded failures were the result of the trial-and-error construction approach. After design concepts were developed and it was no longer necessary to rely on trial and error, there were still failures. They resulted from incorrect use of, or just plain wrong, design concepts. As these types of errors were reduced with advances in science and engineering, a new type of failure emerged—material failures. Properties of materials were misunderstood or misused. Fatigue and brittle fracture of steel and excessive autoclave expansion and alkali-silica reactions in concrete are examples of maternal failures that have been highlighted in recent years.

From the failures of the past, engineers have learned and have corrected and adjusted their approaches to design, construction, and maintenance of engineered structures. It can be said, at least for most of today's civil engineering structures, that we understand how to design them, the materials being used, how to construct them, and how to inspect and maintain them. Then, why have these recent failures occurred? The answer is simple: the quality of designs, construction, and inspection and maintenance programs is not keeping pace with the needs of our aging and deteriorating structures and with the exorbitant cost of failure. One of the main reasons for the situation has been an erosion of the acceptance of responsibilities over the years on the part of all concerned.

Engineers learn from experience and take steps to correct their ways of doing things. Facilitation of this process is the reason for ASCE Manual 73, *Quality in the Constructed Project* (*2*). Engineers realize that something has to be done. The ASCE guide to quality is certainly a step in the right direction. Its use can define design and construction quality in our constructed projects along with an acceptable level of performance.

HOW THE QUALITY MANUAL GOT STARTED

The number of projects suffering significant accidents and failures annually constitutes only a very small percentage of those projects completed each year, and there has not been any significant change in the number and size of failures over the years. Nevertheless, the litigious nature of society and the associated high costs of losses, along with greatly expanded media coverage, have focused these problems in the eyes of

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the public. Partly because of this focus, many members of the civil engineering profession believed that something should be done. Discussions were held on the subject at the Structures Failures Conference in 1983 in Santa Barbara, California, organized by ASCE. These discussions led to a 1984 ASCE workshop in Chicago attended by nearly 100 delegates from the design professions and the construction industry. The idea of a comprehensive guide to quality in design and construction grew out of this workshop. The ASCE accepted the responsibility of producing such a guide.

The ASCE board of directors established a five-member steering committee to manage preparation of the quality guide document and assigned the ASCE managing director of professional affairs to work with this committee. The first step was to develop an outline. In order to facilitate this, available quality assurance and control manuals and other pertinent related material were systematically collected. The result was several filing boxes of references. A consulting librarian was appointed to spend a summer reviewing these documents and prepare a list of key words culled from the tables of contents, the indices, and the texts. This list of key words turned out to be a document more than 70 pages long. One member of the steering committee took this list and developed a first draft of an outline. From this, the steering committee developed a detailed outline covering 24 chapters (later reduced to the present 22). Whereas the original instructions from the ASCE board of direction suggested preparation of a standard, the steering committee decided that standard language would not be used and that the document being prepared would not be a standard. In addition to the outline, a statement of purpose and a list of principal themes for author direction and guidance were prepared.

STATEMENT OF PURPOSE

The following objectives were formulated by the steering committee:

1. Provide guidelines and recommendations for owners, design professionals, and constructors on how to provide quality in constructed projects;
2. Clarify and define the roles, responsibilities, and limits of authority for owners, design professionals, constructors, and other participants in constructed projects;
3. Set forth general and specific definitions of critical words and phrases; and
4. Stress the importance of concepts and practices that improve quality in constructed projects.

The manual is intended for all parties connected with or interested in the design and construction process. It is not in itself a technical document or a guide strictly for design professionals. Its language, style, and format are intended for nonindustry readers as well as for professionals and practitioners. Interested readers will include owners, engineers, architects, constructors, developers, users, operation and maintenance personnel, testing personnel, suppliers, inspectors, and subcontractors. It is also intended for attorneys, government officials, university professors, students, judges, and legislators.

PRINCIPAL THEMES

The principal manual themes were as follows:

- Definition and assignment of responsibilities;
- Importance of teamwork;
- Understanding of requirements and expectations;
- Importance of contract provisions defining the exceptions and obligations of the project team members;
- Principles of good communication;
- Owner's selection processes for project team members;
- Need for adequate scope, time, and liability protection;
- Procedures for design and construction;
- Organizational, management, and administrative practices;
- Conflict avoidance and the value of mediation;
- Benefits of peer review;
- Participation of the design professional during construction and start-up;
- Construction contract submittals, including shop drawings; and
- Standard form of agreements and other documents.

WRITING PROCESS

Once the outline, statement of purpose, and principal themes were completed, the steering group selected approximately 40 authors representing all parties associated with constructed projects—owners, developers, design professionals, contractors, insurance underwriter representatives, and facility operators. In addition, approximately 90 reviewers were selected to review individual chapters. The authors and reviewers are an outstanding group representing the top personnel in their professions. At the same time, the manual key staff was enlarged to include a managing editor and a technical editor. After the workers had completed their assignments and individual chapters had gone through several internal reviews and rewrites involving the reviewers and the steering group, a more formal review process was initiated.

REVIEW PROCESS HISTORY

The steering committee completed the first draft of the manual in October 1986. The second draft was completed in April 1987. From April to June 1987, more than 1,000 copies of the second draft were distributed to members of the design and construction industry across the United States, along with the approximately 50 other umbrella organizations associated with constructed projects. The recipients were invited to review the document and submit comments on its contents. The reviewers of the second draft represented nearly every segment of the design and construction industry and included representatives of ASCE, related professional societies and trade organizations, private firms, local and national government, universities, trade publications, and law firms. The reviewers submitted more than 800 pages of comments, which were reviewed by the steering committee and incorporated into the second draft text as appropriate.

During the review process, the steering committee developed an executive summary and a much-needed glossary. After incorporation of these additions, and following major rewriting on the basis of the review comments, a preliminary edition for trial use and comment was prepared and distributed and sold to more than 12,000 individuals and organizations. The readers were advised that this document was a draft and were invited to submit comments. The review period for the preliminary edition extended over the 18 months from June 1988 to December 1989.

PRELIMINARY EDITION TEXT

The preliminary edition document covered 192 pages. The steering committee was not entirely satisfied with this edition; it had been difficult to incorporate the many constructive comments and criticisms received during the interval review process. Many comments were received after the deadline and could not be incorporated at all. There was dissatisfaction about the overlapping areas that resulted from using some 40 authors. However, it was decided to issue the preliminary edition on schedule. Since it was clearly a draft, changes could be made later.

The preliminary edition included 24 chapters and a glossary. After an introductory chapter, two chapters were devoted to the benefits of quality to the owner and to his expectations and objectives. An important chapter on the communication and coordination process followed. Nine succeeding chapters covered selection of the design professional and were specifically related to procedures of design practices. Following design, another nine chapters discuss the construction process from planning, selection of a contractor, and contract administration through project start-up. This section included an important chapter on shop drawings and responsibilities. The preliminary edition closed with chapters on operations and maintenance and risk avoidance.

INITIAL IMPACT

As previously noted, approximately 12,000 copies of the preliminary edition were distributed. The comments received were voluminous in proportion to this massive distribution. The major comments received included the following:

- The text was too long. However, in most cases where this comment was made, there were also suggestions about expanding specific areas.
- There was duplication of material as well as conflicts in text from chapter to chapter.
- The title received many comments. The term "Manual of Professional Practice" was objected to by many.
- The text was overly oriented toward large design firms and large projects at the expense of small firms and small projects.
- There was the potential for increasing the design professional's liability if the manual were published. There were objections to specific language and to manual support of practices that were not necessarily standards throughout all geographical regions of the country.
- Specific issues were not covered adequately, such as the role of regulatory agencies, the site safety issue in the construction process, and the negotiated construction contract as opposed to competitive bidding.
- The educational nature of the manual should be stressed.

The foregoing only summarizes some of the common themes running through the thousands of comments received. There was also general support for the project. In general, the comments were constructive. However, apprehension was repeatedly expressed regarding the potential liability problems that could occur if the manual were officially issued by ASCE.

REVISED TEXT

On the basis of the comments received on the preliminary edition, the steering group decided on the following changes:

- Reduce the text from 180 to approximately 120 pages by pruning, condensing, and avoiding repetition and conflict.
- Place appendices at end of text.
- Rewrite text using descriptive rather than prescriptive language.
- Emphasize the aspirational and education aspects of the manual as well as emphasizing that it does not represent existing standards of practice.
- Use the generic format throughout.
- Remove the bias toward the design professional.
- Emphasize teamwork among participants while recognizing divergent objectives.
- Emphasize that laws and contracts govern assignment of responsibility.
- Stress site safety.

In addition to these general revisions to the text, specific changes to individual chapters were made, including the following:

- Reduce the executive summary to three or four pages stressing the owner's phase, the design professional's phase, and the constructor's phase of the work.
- Condense the section on selection procedures, reword using more positive language, and condense discussion of the two-envelope system of selection.
- Use the American Institute of Architects' rewrite of Chapter 10, which changed language from prescriptive to descriptive for entire volume.
- Combine the chapters on the use of computers.
- Emphasize the role of construction managers in the chapters on construction.
- Include negotiated contracts as well as competitive bidding in the section on selection of a constructor.
- Cover all types of shop drawings. (This was not done.)
- Rewrite the section on risk avoidance to eliminate design professional bias, and delete the discussion on insurance and bonds.
- Provide a new chapter on quality assurance and quality control.
- Change the title to eliminate the term "Manual of Professional Practice."

With these changes, the preliminary edition was rewritten and a first edition published. The preface emphasized the aspirational and educational nature of the document. To eliminate the fragmented approach of the preliminary edition, which used some 40 authors, all revised text was prepared by the managing editor and the technical editor. Authors were then requested to review the revised chapters.

FIRST EDITION

The revised manual incorporating these changes was reduced from 24 to 22 chapters and from 192 to 145 pages of text. The same format of delineating the owner's, design professional's, and constructor's responsibilities was not changed although there was some reorganization of the material to provide a better flow.

The preface to the first edition, designated hereafter as the Guide (*2*), summarizes what the Guide is and what it is intended to do. The following is from the preface:

> This Guide has been written for all participants in a construction project, and describes a desirable *process* for project delivery from conception through design, construction, and operations start-up. It is a compendium of what the design and construction process should be to enhance quality. It contains descriptions of techniques, systems, methods, and procedures as contributed by numerous authors experienced in the process. It is not all-inclusive, and other options of equal or superior merit not mentioned in the guide may exist or may be developed.
>
> The Guide discusses numerous aspects of the process likely to be pertinent for major projects; for smaller projects, some of these aspects may need only limited attention or may not apply at all. Likewise, a description of multiple staff *functions* for a project is not to be taken as a need for multiple staff *positions*, because, for many smaller projects, the functions often can be accomplished by a single individual.
>
> The Guide is intended to be educational in nature, with the belief that embracing the philosophies and processes it describes will contribute to the quality of a project. It is not, however, a complete codification of practice within the construction industry, nor does it represent a "baseline" or minimum standard for correct or appropriate project development. Rather, it is intended as an aspirational document. The authors and editors had the benefit of a variety of resources, including printed materials and the comments of several hundred reviewers. The attempt was made to select from these sources and present factors contributing to quality in design and construction, with the hope of stimulating readers to identify areas where the levels of their practice can be raised.
>
> The Guide should be used with care, since there is no satisfactory substitute for the exercise of prudent judgment by the owner, designer, and constructor. Moreover, the specific contractual provisions involved in a project may vary the procedures suggested in this Guide and, in that case, the specific contractual provisions govern.
>
> Finally, the Guide will be a living document, subject to ongoing review coordinated by an oversight committee, and to revision at regularly scheduled intervals.

AREAS FOR IMPROVED QUALITY

ʻ is anticipated that the ASCE Guide will have a future impact construction. Specific areas where changes are needed that upported by the Guide's recommendations are outlined ter.

Design Professional Involvement in Construction

Most municipal, state, and federal agencies deliberately do not assign construction inspection contracts to the firms that designed the projects. There are several reasons for this policy, but the result is that quality in the constructed project is definitely compromised. The Guide takes the position that the design professional of record should be involved in the construction process and, indeed, advocates full involvement. Most professionals support this position; the only negative facet is the owner's unwillingness to pay adequately for this involvement. During the Guide review process, many federal agencies, though not practicing such a policy, supported the concept of the design professional's involvement and have acknowledged its positive effect on quality.

Project Peer Review

The Guide supports the concept of project peer review. One of the problems with this procedure is the possible incurrence of liability by the peer review firm or organization. The Guide attempts to address this issue and to define liabilities appropriately. Project peer review is presently seldom practiced; however, the advantages thereof and its impact on quality are obvious. Another problem has been the owner's reluctance to pay for such a review. Again, the Guide emphasizes the cost-effectiveness of such procedures with the intent of educating owners to institute project peer reviews.

Firm Peer Review

Whereas firm peer review is a growing practice, the full endorsement of this procedure by the Guide is expected to accelerate the process. Obviously, a well-run firm that has established acceptable managerial and administrative practices fosters better designs and improved contract documents than other firms.

Quality Assurance and Quality Control

Quality assurance and quality control programs and procedures are encouraged by the Guide for both the design professional and the constructor. The need for the owner's recognition of the value of such programs is pointed out, and the cost-effectiveness of the owner's paying for such activities is emphasized. Such programs are certain to have a major impact on quality in the constructed project.

Shop Drawing Responsibility

Not withstanding the legal liability assumed by a detailer preparing shop drawings when he designs connections, and regardless of any specification requirement that a licensed professional engineer be used, the Guide clearly states that the design professional of record has full responsibility for the extensions of his designs that are shown on the shop drawings.

This responsibility cannot be assigned or transferred or abrogated by exculpatory language in shop drawing approval stamps. The result of this clear definition of shop drawing responsibility is that design professionals will assign experienced personnel to check shop drawings rather than delegating such activities to junior and perhaps unqualified members of the staff. The result should be a positive impact on the quality of construction.

Equitable Compensation

As noted in several preceding items, the Guide emphasizes the cost-effectiveness of various practices and procedures and encourages owner recognition of the need to adequately compensate both the design professional and the constructor for following them. It is well recognized that small investments in these areas pay off handsomely in terms of quality, the meeting of objectives, and final total project costs.

Definition of Responsibilities

While responsibilities are assigned contractually as well as being legal obligations, the Guide suggests clearly defined areas of responsibility for the several parties involved in the constructed project. This approach has already motivated several organizations that prepare standard contracts to review their documents with the intent of revising them to reflect similar positions. It is hoped and anticipated that the Guide will provide the impetus for governmental agencies to do the same.

SOME OUTSTANDING ISSUES

Comments by National Society of Professional Engineers

After the Guide was published, the National Society of Professional Engineers (NSPE) reviewed the document again and made several suggestions for future editions.

Preface

NSPE recommends that the preface should imply that the Guide represents an absolute, that the Guide be referred to as a "publication" rather than a "guide," and that reference to the Guide as an "aspirational document" be deleted.

Chapter 21—Shop Drawings

The design engineer of record should specify the type of inspection required, and such inspection should be performed by inspectors approved by the design engineer. This statement was addressed mainly to construction components fabricated off the construction site.

Language should be added dealing with the problem of temporary construction loads, which could compromise the structural integrity of the facility either during or after construction. The design engineer of record should either approve the temporary construction loads proposed by the constructor or include, in the specifications, stated load limits that apply during the various stages of construction.

Independent testing of construction materials and components should be performed in a laboratory approved by the engineer of record and employed by the owner, to ensure independence of test results.

Chapter 5—Procedures for Selecting the Design Professionals

Add the following to the Introduction to incorporate greater emphasis on total quality management techniques:

> The capital, operation and maintenance costs, along with the reliability and life cycle of the constructed project, are determined in the design process. Seldom will the least-cost design result in the minimum capital or life-cycle cost for the owner. Modern competitive practices of total quality management have shown that a quality oriented teamwork approach between the owner and his engineering design firm will result in maximum owner satisfaction. Lowest design cost will not result in the best quality or minimum project costs.

Add the following to the Section 5.2, Basis for Selection:

> Design services during construction should be clearly defined. A cost allowance must be made for the design professional to be able to assure that the constructed project is meeting the design specifications. Critical hold points during construction should be specified by the designer and design compliance should be verified by inspectors agreed to by the designer. Some construction means and methods including temporary material or equipment loads on the partially completed structure could compromise the structural integrity. The design engineer should participate in the review and approval of any construction means and methods which require engineering knowledge and analysis of the facilities structures load limits.

Comments by American Consulting Engineers Council

After the preliminary edition was published, the American Consulting Engineers Council (ACEC) board of directors voted to reject it. After the first edition was published, the ACEC board of directors voted not to reject the Guide, by a vote of 461 to 359. The closeness of this vote emphasizes how practicing engineers feel about the Guide. A large number of ACEC members are essentially "one-man" firms. These firms do not have the staff to check designs and represent themselves on the construction site, nor do they necessarily want to add staff so that these things can be done. Working for themselves, they have no problems with social security, unemployment taxes, employee benefits, and so forth. They may be simply taking a position against anything that threatens their status quo.

In addition, a large number of ACEC members stress the liability that may be associated with a published, authorative ASCE Guide. They fear the Guide will be used against them in lawsuits. This argument may possibly be a cover-up for not wanting to perform quality work as defined by the ASCE

Guide, on the basis of the belief that clients will not pay for such performance.

BENEFITS

Whereas it is expected that adoption of the principles set forth in the Guide will foster quality in the constructed project, there are several important corollary benefits:

- The first is, obviously, fewer failures—both during construction and after the project is finished.
- There should be a reduction in change orders during construction. The owner is never happy about change orders, and the constructor is never happy with the compensation for them. The design professional, who is commonly caught in the middle, will also benefit.
- There will be less litigation. At present a large number of construction contracts end up with claims that must be settled in arbitration or in court. Reduction in claims is a major saving to all parties involved in the constructed project.
- Teamwork will be enhanced by designing and building projects without extensive problems, and a closer, more trusting relationship will develop between the interested parties leading to increased cooperation on constructed projects.
- Finally, increased quality in design and construction will result in better-satisfied owners, whose objectives and expectations have been met, and better-satisfied design professionals and constructors, who can take increased pride in their work.

REFERENCES

1. H. Petroski. *To Engineer Is Human.* St. Martins Press, New York, 1985.
2. *Quality in the Constructed Project.* Manuals and Reports on Engineering Practice 73. ASCE, New York, 1990.

Publication of this paper sponsored by Committee on Construction of Bridges and Structures.

Quality in the Constructed Project: Designer's Viewpoint

GERARD F. FOX

Controversial provisions contained in ASCE Manual 73, *Quality in the Constructed Project*, are outlined and commented on from a designer's viewpoint. The provisions include design professionals' participation during the construction phase of a project, site safety responsibility, design professionals' responsibility for contractor submittals, and procedures for selecting a design professional. Also included are suggestions for computer data retention, use of large data bases, and need for a software quality certification program. The peer review process is briefly explained and is recommended for use since it adds to the quality of the constructed project.

ASCE Manual 73, *Quality in the Constructed Project* (*1*), serves as a guide for owners, designers, and constructors. As stated in the manual, the purpose of the Guide is

- To achieve quality in the constructed project;
- To provide guidance for establishing roles, responsibilities, relationships, and limits of authority for project participants; and
- To stress the importance of concepts and practices that may help achieve quality in the constructed project.

The Guide is a comprehensive document that details, very well, the steps from initiation to completion and operation of a project. It is not another book to be put on the shelf and forgotten. It is important that it be implemented and used by all in the construction industry. Those who do not agree with some of the provisions can work to have them changed. They can also suggest additions to be included in the next edition of the Guide. It will be a living, working document that, it is hoped, will be revised and updated every 3 to 5 years.

From a designer's viewpoint, the Guide is a valuable document because it outlines not only the designer's duties and responsibilities but those of the owner and constructor as well. Most experienced designers would probably note that much in the Guide was well known and presently a part of the construction process. However, they would also welcome the fact that there is now a written document that they can refer to. The Guide is excellent for study by young designers and is already being used as a textbook in several engineering colleges.

Whereas most of the provisions of the Guide are readily accepted by all those participating in the constructed project, there are some that are controversial and deserve some comment.

HNTB, 3 Whitehall Boulevard, Garden City, N.Y. 11530.

CONSTRUCTION SERVICES

The Guide contains a recommendation that the design professional be fully involved in the construction phase of the project. Why should the design professional participate during construction? One obvious reason is that design team members are the most knowledgeable about important design aspects and the intent of the design in satisfying the requirements of each discipline as well as project directives. But there are other reasons. The design team is proud of what it has accomplished on paper and has a greater interest than others in ensuring that the project follows the design intent and quality standards. Site visits not only allow the design engineer to see that the work is progressing as planned but also educate the engineer to appreciate problems that arise in the field. The design engineer is also readily available to attend site meeting with the contractor and promptly answer any questions on design interpretation. Communication is best and most productive when the site engineers and design team are members of the same firm.

Construction inspection services for bridge projects are usually provided by the consulting firm that executed the design, another consulting engineering firm or construction management firm, or the owner, which for bridge projects is usually a state or city government.

The reasons usually given for using a firm other than the design professional's for construction services include a desire to spread fees among more engineering firms, dissatisfaction with the work of the design consultant, or the idea that any design error would be hushed up and buried by a site team that belonged to the same firm as the design team. It appears that any significant design errors will become known by the owner because usually these errors result in a claim for extras by the constructor.

Some city and state governments have excellent construction service departments. They are familiar with all of the quality control standards established by the state and know the capabilities and limitations of most of the contractors working for the state.

However, some city and state governments are under severe budget constraints and sometimes cannot supply knowledgeable site engineers. On one bridge construction project the owner sent a highway engineer to provide the construction inspection services. In addition, they usually do not have the experience to adequately staff a large project.

The design professional who is not invited to participate in the construction phase should probably seek a hold harmless clause in the contract with the owner. Some engineers will not accept a design assignment unless the contract provides for construction involvement.

The writer endorses the manual's recommendation that the design engineer, if possible, be contracted with to provide the required construction services.

The manual clearly spells out the responsibilities of the owner, the design professional, and the constructor. It states that the constructor is responsible for means, methods, techniques and sequencing of construction, and planning and enforcement of site safety programs. It further states that the designer has no authority over or responsibility for these items.

These are strong statements, and one must remember that the manual is a guide, and sometimes deviations will need to be taken to get the job done. For example, on a major bridge project the design engineer may need to provide guidance to the contractor to develop a satisfactory erection scheme, even if the contractor has hired another engineer to assist in developing an erection scheme. In so doing, the design engineer must weigh the legal responsibilities that may be incurred against the need to prevent unnecessary delay of the project.

In addition, it is sometimes necessary for the engineer to sketch solutions for details that are then given to the contractor for full development and subsequently submitted for approval by the contractor.

SITE SAFETY

The construction industry is the most hazardous of any other industry in the United States. One in seven construction workers is injured on the job each year (*2*). There is an alarming tendency among some government agencies and other owners to require that the engineering firm providing construction services also be made responsible for the job safety of the contractor's employees. In general, they are not satisfied with the present state of site safety conditions and believe that, by having the engineering firm in charge of job safety, safety rules will be enforced and the number of accidents reduced. It seems apparent that this cannot work, since the engineering firm's resident project representative has no direct authority over the contractor's employees.

Engineers better take care and seek legal counsel before signing a contract that requires even only an approval of a job safety plan. An interesting recent court case has ruled against an engineer on this issue (*2*).

One of the most troublesome liability issues in providing construction services concerns workmen's compensation. Workmen who are injured are restrained by workmen's compensation from bringing suit against the contractor. They are not so restrained in regard to the consulting engineer, and they usually initiate suits against the engineer. The manual is clear that the worker's safety is the concern of the contractor. I do not think that this is enough. The engineer needs to be protected in the same manner as the contractor is by workmen's compensation.

CONSTRUCTOR SUBMITTALS

The responsibility of the design professional in constructor submittals, including shop drawings, has always been vague and controversial. The Guide states:

> The professional services contract between the owner and design professional, who may also be the structural engineer of record, and the construction contract between the owner and constructor should define clearly the authorities and responsibilities of each party, including design services, scope and purpose of contract submittal review by the design professional, and scope of work to be performed by the constructor and subcontractors, such as fabricators, detailers, suppliers, and manufacturers, so as to avoid misunderstandings and vague, implied, or implicit responsibilities.

As a minimum, the design professional should review, approve, and be responsible for any design that the contract required the contractor to accomplish.

Further, the Guide states:

> The design professional reviews submittal for conformance with the design concept of the project and information given in the construction contract documents, but does not review those aspects of a submittal that pertain to the construction process, such as the means, methods, techniques, sequences, and procedures of construction; detailing dimensions; fit or erectability in the field; or safety precautions and programs.

The Guide is silent on submissions of contractor's alternative designs, but it appears that the design professional should review and approve such designs. As far as responsibility is concerned, a good rule to follow is "a firm must be responsible for its own work." This would ensure that everyone concerned have a good quality assurance/quality control program in place. Top management must enthusiastically support such programs and be serious about their implementation. If they are not, how can they expect the rest of the firm to take the programs seriously?

DESIGNER SELECTION

Chapter 5 of the Guide is entitled "Procedures for Selecting Design Professional." The recommendation in the Guide is as follows:

> Design professionals submit statements of interest and qualifications in response to an owner's invitation and statement of requirements for a specific project. The responses are evaluated by the owner according to previously announced selection criteria. Often, an owner conducts personal interviews with the three design professionals who appear to be most qualified for the assignment.
>
> After the design professional is selected on the basis of qualifications to meet project requirements, contract negotiations between the owner and design professional are initiated. During these negotiations, scope of services, schedule, compensation, and other contractual matters are defined, agreed upon, and documented in a written contract. If the owner and design professional are unable to reach an agreement, then the negotiations are terminated and the owner initiates negotiations with the next most qualified design professional.

It has been proven many times that following this procedure best serves the owner's interests, expectations, and requirements.

Price bidding for the procurement of professional design services is not recommended. Bidding discourages innovation and the study of alternatives. The scope of work is usually deficient, which leads to claims for extra work and extension of time for completion of the contract. In addition to these reasons, the low bidder may be only marginally qualified to do the work.

Another method of procurement of professional design services is called the two-envelope system, because three to five firms are requested to submit technical and price proposals but keep them in separate envelopes. The technical proposals are evaluated first and a firm is selected as having the best. Only then is the price proposal looked at and negotiations initiated. The two-envelope system is also not recommended because it requires unnecessary work and expense by the firms not selected.

COMPUTER USE

The Guide chapter on "Project Quality Through Use of Computers" deserves careful study by all concerned with the construction process. Experience has shown that relying on archival storage of computer data and programs and then being able to reproduce computer output years in the future is fraught with difficulties. Hardware, software, and operating systems change and are updated often without much regard for past use. Hard copies of as-built drawings of a construction project should be retained as well as the design and material specifications used. Design and detailers' calculations need not be saved upon completion of a project since they can be reproduced as necessary probably more accurately, with better programs in the future. Future editions of the Guide may well give guidelines as to the length of time various documents should be retained.

There has been an explosive growth of information that design professionals must somehow cope with. Most design firms have small libraries, which are quickly outdated. Designers need to become familiar with and use expert information retrieval systems to access commercial computer data bases to identify technical publications that might help them. ASCE has such a computer data base of all its publications.

The Guide mentions quality certification programs and sources of information on acceptance standards but none concerning computer use. There is a need for a quality certification program for software. Such a software clearing house would be valuable and save time and expense on the part of design professionals. In addition, there would be less chance of errors attributable to computer software use.

PEER REVIEWS

The Guide notes that peer reviews are gaining acceptance, and they have successfully advanced quality in the construction process. Peer reviews are basically examinations of the quality of an organization's structure, or with what quality a project is managed and designed. It is important that such a review be done by an experienced independent professional, who could be an outsider or an insider and who could well be from another office of the firm. Such reviews could result in suggested changes in an organization's structure and the identification of problems of a current project, thus allowing immediate corrective action to be taken. The Guide goes into great detail explaining the implementation and benefits of peer reviews. Project peer reviews are usually paid for by the owner. They should be used more often, since their implementation will add to the quality of the constructed project.

WHAT TO DO

The main purpose of this paper is to interest you and your organization in obtaining a copy of the Guide, *Quality in the Constructed Project*, studying its provisions, and implementing it in your organization. Your suggestions for improving editions of the Guide will be most welcome and carefully considered.

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Constructor's View of Quality in the Constructed Project

William R. Nash

A contractor's view of quality in the constructed project is given from two perspectives: estimating/bidding and actual construction. Contractors believe that quality should be a factor inherent in the prebid documents, constructability review, safety programs, and conflict avoidance. The constructability of a project should be reviewed concurrently with design. Effective safety programs for projects start with the owner. Treating safety as an incidental in a construction project is an error with grave consequences. Conflict avoidance requires detailed plans, special provisions, and specifications that include a fair allocation of risk included in the following clauses: changes, time extension, geotechnical information, differing site conditions, supervision of work, liquidated damages, variation in quantities, claims, and disputes.

Rehabilitation and expansion of the largest and most efficient highway transportation system in the world are necessary. The system is gridlocked in urban areas because of increased traffic demand and decay due to age and neglect. The work at hand is to replace, upgrade, design, and construct highways, bridges, and associated systems across the nation.

Our task as engineers and contractors is to construct safe and economic projects using quality contract documents to build quality projects.

QUESTIONS

"The true measure of a civilization is in how it maintains itself." What kind of a grade for quality would we give ourselves on a report card for the maintenance of our civilization in the categories of education, design, financing, specifications, materials, construction, and dispute resolution?

With the quality of some past materials and workmanship exceeding those of today, what distinguishes quality in the worlds of engineering and construction 20, 50, or 100 years ago?

THE "QUALITY" MANUAL

ASCE Manual 73 (*1*) is an attempt to define aspects of construction project quality. It is understood that there is no wise man atop the mountain with the truth about quality. Quality management means "conformance to requirements." "The cost of quality is the expense of doing things wrong." "Non-quality is nonconformance." The difficulties in the implementation of "quality management" are summarized by Crosby (*2*).

> Unfortunately, the business of quality management is not all that easy. It isn't all that hard either, but it does encompass more than a single gulp of philosophy. It also requires unblinking dedication, patience and time. The problem of quality management is not what people don't know about it. The problem is what they think they do know.

CONTRACTOR'S PERSPECTIVE

A contractor's view of quality in the constructed project is given from two perspectives: estimating/bidding and actual construction.

Contractors find the following typical problems with construction projects and the plans and specifications (*3*):

1. Constructability deficiencies due to incomplete, erroneous, or nonexistent details;
2. Shop drawing approval; and
3. Owner cooperation to resolve problems.

A contractor, from the initial viewpoint of estimating, should review the contract documents and assess the project throughout the plans and specifications. An initial contractor review lists the following: scope of work; scheduled duration (completion date); type of contract (lump sum, unit price, etc.); amount of liquidated damages; classified or unclassified excavation; differing site conditions; type of changes clause; type of damage for delay cause; geotechnical report—quantity and location of borings, test wells; equipment requirements for temporary structures; review of the project's special provisions; constructability; erection sequence; and so forth. From this list a contractor ascertains whether it is in the company's best interest to bid the project. This decision weighs the project risk, the identity of the owner and the owner's engineer and inspection agent, the competitive market, the current backlog, current bidding opportunities, and the quality of the plans and specifications.

A review of the plan's prebid looks for details and complete specifications. A list of questions is compiled to clarify the drawings in order to estimate the cost of construction. Quantity takeoff is performed and quantity comparisons made. The submittal of prebid questions is made by telecom or formally by mail or fax to the owner's engineer.

Although we exist in an electronic business age, the prebid process of drawings and specification clarifications can be in a "horse and buggy" age. A contractor sees a wide variation

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of quality in the engineer's prebid response to requests for information and clarification.

Often plan quantities in bid documents are incorrect. In one state—1 week before bid date—a contractor is told, "There is not enough time to issue an addendum—bid the plan quantity." In another state, the revised quantity and proposal sheet would be faxed to all plan holders as late as the day of the bid.

Often the bid documents include information or drawings that contain items stamped with disclaimers such as, "This drawing is a conceptual schematic construction only. The contractor shall submit the detailed construction scheme for approval by the engineer" (*3*) attempting to make them invisible. Typical examples of these "nonexisting" attachments are geotechnical reports, boring logs, bridge erection procedures/sequences, and temporary shoring. An example of the language of invisibility is as follows: "The borings and project geotechnical report are available upon request for review at the engineer's office. These items are for the contractor's information only and are not a part of the bid documents" (*3*).

CONSTRUCTABILITY

The manual (*1*) contains two short paragraphs referencing constructability reviews. The impact of the suggestions made in these two paragraphs is potentially great. Constructability is unfortunately a cosmetically applied buzzword even though it is known to be of critical importance.

Construction and erection sequences are often afterthoughts in assembling a set of bid documents. The project's constructability should be reviewed concurrently with design.

It is common for the erection/construction sequence drawings to include a disclaimer stating either that they are conceptual only or that it is the contractor's responsibility to erect the bridge safely. The following is an example of a disclaimer placed on an erection sequence drawing: "The safe erection of the bridge is the sole responsibility of the contractor. The erection sequence shown in the contract plans is schematic only. The contractor shall prepare a complete erection analysis." The plans and specifications place extensive construction engineering responsibilities on contractors with little or no time for detailed analysis before bid.

Contractors believe that the owner and the designer are responsible for constructability and that they should provide one complete erection scheme that considers construction erection stress conditions. A contractor's alternative erection sequences would be his responsibility (*4*).

The designer "should state unequivocally that all parts of the permanent structure have been designed for loading conditions that will arise during construction if his method and sequence is followed" (*5*).

SAFETY

All parties to the construction process must be cognizant of the personal and monetary costs incurred as a result of construction accidents.

> The Laborer's Health & Safety Fund, N.A. recently released a report stating that the construction industry is the most hazardous and has the highest overall injury rate of any industry in the U.S. One in seven construction workers are injured on the job each year. In 1989 alone, the industry lost more than 6.3 million workdays due to accidents and injuries. And, while only 6% of American jobs are in construction, the industry accounts for over 20% of on-the-job deaths (*6*).

The manual (*1*) states that the contractor has primary responsibility to initiate a job safety and first aid program. In the real world, additional safety responsibilities exist for the owner and the owner's construction inspection engineer and designers.

There is debate about the involvement of the owner, design professionals, and the contractor in reference to safety. All parties ask for indemnification of their acts and omissions.

For the record, if you walk a job site in today's world and see and fail to act upon witnessing an unsafe act—no matter what your contractual responsibility to the project—you are responsible.

Effective safety programs for projects start with the owner. Treating safety as an incidental in a construction project is an error with grave consequences.

CONFLICT AVOIDANCE

The best way to avoid conflicts and subsequent litigation is to use common sense in the project design and bid documents. This application of common sense would include a detailed site investigation, use of unit prices, and equitable contract language for both changed conditions and delays. "Experience has demonstrated that if bidders are assured that the contract provides reasonable means to resolve contractual problems as they arise, the owner will receive lower bid prices" (*7*). Conflict avoidance requires impartial and objective dispute resolution. Pride of authorship and the application of standard specifications must yield to a team (owner, designer, contractor, and construction engineer) building a project from detailed plans, special provisions, and specifications that include a fair allocation of risk included in the following clauses: changes, time extensions, geotechnical information, differing site conditions, supervision of work, liquidated damages, variation in quantities, claims, and disputes (*7*).

CONCLUSION

The existence of the manual cannot be debated. The content must be understood, discussed, revised, and/or deleted by owners, engineers, and contractors in the construction of safe and economic projects. To quote from the manual's frontispiece, " 'Construction' quality is never an accident. It is always the result of high intention, sincere effort, intelligent direction, and skillful execution. It represents the wise choice of many alternatives" (*1*).

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ASCE Quality Guide: Sword or Shield?

ROBERT J. SMITH

ASCE Manual 73, *Quality in the Constructed Project*, has been criticized as potentially creating new legal standards of care, particularly for design professionals. In reality, adherence to the recommendations and guidelines should help, not hurt, the design professional. By way of comparison, the use of codes, standards, handbooks, and even legislation as a standard of care for design professionals has been addressed frequently by the courts with predictably mixed results.

The conception, development, and issuance of ASCE Manual 73, *Quality in the Constructed Project* (hereafter sometimes referred to as the "ASCE Guide" or "Manual 73"), generated an intense debate over the legal implications of its content. The concerns expressed by legal commentators are identified and discussed and their merit in the present context is evaluated.

(The author participated in the development of Manual 73 as a chapter author and as a reviewer. He declined to participate in the legal forum convened by ASCE in the belief that such participation could potentially detract from the legal forum's objectivity.)

CONCERNS—QUALITY AND LIABILITY

The ASCE Guide was developed to provide a means of enhancing quality. It was intended to be a positive, constructive, and affirmative effort. From the beginning some contended that the ASCE Guide would become in effect a sword—a weapon to be used against them in professional liability lawsuits. That is, there was a fear that nonconformance with the recommendations of the ASCE Guide would result in a finding of negligence. This was a realistic concern. The drafters, the steering committee, and the editors were sensitive and responsive to that concern, as evidenced by the final manual. Thus, it was made clear that the ASCE Guide is an aspirational document, not a minimum.

In addition, ASCE took these concerns to heart by establishing a legal forum of leading construction lawyers and professional liability insurance executives from across the nation. The forum was charged with reviewing the ASCE Guide for unintended liability exposure. In addition, ASCE retained John R. Clark, longtime counsel to the Engineers Joint Contract Documents Committee, to provide a detailed review of the early drafts of what was to become Manual 73.

STANDARD OF LIABILITY—GENERALLY

Now that Manual 73 is a reality, it is useful to assess whether it is a potential sword or shield.

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Recovery from a design professional, whether sought by the disappointed project owner or an injured third party, requires proof of negligence. Most often this comes in the form of expert testimony. The standard of negligence as stated by one court decision is as follows:

> In performing professional services for a client, an engineer has the duty to have that degree of learning and skill ordinarily possessed by reputable engineers, practicing in the same or a similar locality and under similar circumstances.
>
> It is his further duty to use the care and skill ordinarily used in like cases by reputable members of his profession practicing in the same or a similar locality under similar circumstances, and to use reasonable diligence and his best judgment in the exercise of his professional skill and in the application of his learning, in an effort to accomplish the purpose for which he was employed.

In addition to expert testimony as to what was appropriate professional conduct under project-specific circumstances, plaintiffs have sometimes been able to rely on a design professional's failure to comply with a code, standard, or handbook as prima facie evidence of negligence.

This concept was the basis for one of the most fundamental concerns of early legal critics of Manual 73. The claim was that the ASCE Guide would be looked at as a minimum and that failure to follow its provisos might constitute a legal finding of negligence.

Given the normal standard applied to find a design professional liable on a negligence theory (e.g., failure to adhere to the standard of due care under the circumstances), reservations concerning a publication that could be characterized as a standard can be appreciated. To be sure, there can be no guarantee or assurance that there will not be attempts to use the ASCE Guide in such a fashion. But, as will be discussed, the chances of this being successful are not great.

ASCE GUIDE NOT A CODE OR STANDARD

The question of whether failure to comply with an organization's practice recommendations, such as those contained in the ASCE Guide, can be evidence of negligence is an important one. A brief review of potentially analogous case law may be helpful in answering the question. Courts have addressed situations where there has been noncompliance with codes, standards, and handbooks. Manual 73 is clearly not a code or standard; it is most like a handbook.

Design Not Complying with Code Constitutes Negligence

Design of a masonry wall contrary to terms of a municipal building code was deemed to be evidence of negligence in *Johnson v. Salem Title Company*, 246 Or. 409, 425 P.2d 519

(1967). Similarly, failure to comply with a safety provision of the Ten State Standards of the Great Lakes–Upper Mississippi River Board of State Sanitary Engineers was held to be evidence of negligence in *Evans v. Howard R. Green Company*, 231 N.W.2d 907 (Iowa 1975). But, in *Allemeier v. University of Washington*, 712 P.2d 306 (Wash. App. 1985), the court concluded that the failure of the University of Washington to erect a barricade on a campus service roadway as required by the *Uniform Manual for Traffic Control Devices* was not negligence per se.

These cases can be distinguished because the ASCE Guide is not a legally enacted code.

Safety Manual Referenced in Contract

And, in *Mervin v. Magney Construction Company*, 416 N.W.2d 121 (Minn. 1987), the Supreme Court of Minnesota held that the Corps of Engineers' safety manual incorporated by reference into a construction contract did not state the standard of care for negligence purposes. Again, it is not expected that Manual 73 will ever be incorporated into contracts.

Advisory Codes and Standards Not Even Admissible

In *Hackley v. Waldorf-Hoerner Paper Products Company*, 149 Mont. 286, 425 P.2d 712 (1967), it was held that advisory codes or safety standards not having the force of law were not even admissible as evidence of the standard of negligence.

Noncompliance with Architect's Handbook Not Conclusively Negligence

In *Taylor, Thon, et al. v. Cannady*, 749 P.2d 63 (Mont. 1988), the court permitted the AIA *Handbook of Professional Practice* to be used to show evidence of a duty on the part of architects, but held that just because an architect did not comply with a provision of the handbook, the architect was not automatically negligent.

Legislative Enactments

Indeed, even a legislative enactment or administrative regulation is not always conclusive in establishing the standard of conduct. Section 286 of the *Restatement of the Law of Torts* provides as follows:

> The Court may adopt as the standard of conduct of a reasonable man the requirements of a legislative enactment or an administrative regulation whose purpose is found to be exclusively or in part (a) to protect a class of persons which includes the one whose interest is invaded, and (b) to protect a particular interest which was invaded, and (c) to protect that interest against the kind of harm which has resulted, and (d) to protect that interest against a particular hazard from which the harm results.

Court application of this standard has been mixed. For example, in *Macey v. U.S.*, 454 F.Supp. 684 (D. Alaska 1978), it was held that OSHA regulations did not impose a standard of care toward a 4-year-old who drowned in a partially excavated ditch on a construction site. But this should be compared with *Northern Lights Motel, Inc. v. Sweaney*, 561 P.2d 1176 (Alaska 1977), where the Alaska Supreme Court held that a motel's failure to comply with the Uniform Building Code would be prima facie negligence. However, the court noted that this could be overcome by evidence of justification for the nonconforming conduct. But in *Harned v. Dura Corporation*, 665 P.2d 5 (Alaska 1983), the court held that the jury should have been instructed that failure to manufacture a compressed-air tank in accordance with the standards of the American Society of Mechanical Engineers constituted negligence per se.

It is important to note that those standards were incorporated into law. Thus, they are unlike the ASCE Guide.

Compliance with "Standard" Not a Safe Harbor

The reverse of the situation often arises. That is, a defendant uses compliance with a standard as a complete defense. Normally, this is not effective. For example, in *Turner v. American Motors General Corporation*, 392 A.2d 1005 (D.C. App. 1978), the court noted that a bus manufacturer's compliance with federal safety regulations was not dispositive of the question of its alleged negligent design of the bus.

This is certainly not to say that many liability claims could be prevented by applying the suggestion of the ASCE Guide where appropriate. For example, the ASCE Guide should help communication with the owner—which, in turn, will result in more realistic expectations and a better understanding of the engineer's tasks and roles.

MANUAL 73 AS A SHIELD

However, it is unfair to characterize the ASCE Guide as only a sword. In reality, it has the potential to be a much larger and more powerful shield. In other words, it is entirely possible that the ASCE Guide will do much more good than harm. In most instances where design professionals and their insurers have paid dollars for verdicts after trial (the only instance were the legal standard of care is truly applied and tested), there was a valid basis for the verdict. Stated differently, the reason many dollars are paid out by insurers (and their insureds, in ever-increasing deductibles) is that the design professional was indeed found negligent.

Accordingly, it would be much more productive in the long run if greater attention were given to using the ASCE Guide as a shield. This publication identifies carefully thought out procedures directed to the avoidance of quality problems, often by means of affirmative steps. By suggesting practices and policies intended to promote quality, it raises the consciousness of all parties to the construction process.

Manual 73 has the distinct potential to help design professionals avoid the problems that were referred to earlier. The rewards, in terms of potential protection, outweigh the risks.

SUMMARY

Thus, whereas the use of industry and profession and practice publications can never be ruled out in terms of what a plaintiff's attorney might seek to introduce as evidence, it seems that as long as a document does not mandate minimum standards of performance, but rather promotes practices that tend to reduce the likelihood of errors and omissions, they will be more helpful than harmful. There are others who will forever disagree, and do so vehemently. However, it is suggested that such unyielding opponents would have the profession "trash" the AISC Manual, various ACI protocols, and the entire library of AASHTO and TRB technical publications.

On balance, it certainly seems that preventive recommendations such as those of the ASCE Guide should not be discouraged.

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PART II

Construction Management

Use of Linear Scheduling in Transportation Projects

JAMES E. ROWINGS AND FRED RAHBAR

Current practices used to plan, schedule, and monitor transportation projects are reviewed. The results of a survey of state departments of transportation concerning the way contract durations are set and scheduling is practiced are presented. Project characteristics and appropriate scheduling methods are reviewed. One approach for linear scheduling of transportation projects, the repetitive activity scheduling procedure (RASP), is developed. The RASP approach is presented with an example project to illustrate its features. The process can be effective for monitoring and controlling projects that have a few highly repetitive yet interrelated activities. The system allows for a graphical depiction of both time and space in a format consistent with bar charts. Methods of project control and change management with the system are also detailed. The system fills a void between bar charts and critical path methods.

State and other transportation agencies need effective methods to plan and monitor highway construction projects. Approaches that will help promote workable schedules can provide many benefits by reducing overall costs, increasing safety, and shortening project duration. A shorter project duration increases public safety by allowing a highway to open earlier, thus reducing construction zone accident risk. The shorter durations reduce public use costs due to traffic interruptions and improved transportation system quality. Workable schedules promote construction efficiency while recognizing other important objectives for the projects.

Transportation projects vary in size and type to such an extent that it is not practical to use a single scheduling approach for all projects. Large bridge projects may lend themselves to the use of critical path method (CPM) approaches, whereas small projects may require only a bar chart to identify the controlling work items. Many of today's projects involving reconstruction of highways are sufficiently complex to require an approach beyond the bar chart. The CPM approach could be used, but it introduces rigid logic, which, in reality, does not exist. Determination of the best approach for scheduling a project from all of the methods available requires analysis of the project characteristics and needs for planning and control.

Many transportation construction projects are characterized by repetitive operations. Transportation construction projects are repetitive in nature, executed by a series of sequential operations repeated in each part or section along the length of the roadway. The projects are mostly horizontal rather than vertical, progressing along a centerline of the roadway in a linear fashion. We term these projects linear in nature. Typically they are made up of a few controlling or critical work items whose criticality is determined by a combination of the inherent physical logic and the definition of quantity for a particular item of work.

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Preliminary study identifies two promising approaches for scheduling projects with these characteristics. The approaches include the line-of-balance and linear scheduling method, which have been developed and used in several countries. Linear scheduling techniques are the most suitable methods for overall management of transportation projects (*1*). A preliminary survey of literature indicates that the use of linear scheduling for highway construction in the United States is very limited, and its use has not been well accepted as with CPM and bar chart (*2,3*).

Bar charts and the network appear to have several shortfalls when it comes to many transportation projects. An alternative is needed for transportation construction projects. It should be possible to simulate the effects of varying productivity rates and to measure the effects on the schedule. An approach with some logic between operations but with less rigid logic than is possible with CPM is needed.

On the basis of prior research by Herbsman, there is no one rigid scheduling technique that can be applied for every transportation project. Several different methods, including bar charts, CPM diagrams, and linear (line-of-balance) schedules, can be appropriate depending on the project characteristics. The scheduling procedures must be developed and tailored to each specific project according to its type, size, and complexity. The specification for scheduling should communicate the requirements that will ensure the timely information for control purposes and the information needed to effectively and fairly deal with schedule issues during the course of the project.

Recognizing that the current scheduling approaches are not ideal for all projects, this paper describes a scheduling procedure that combines the features of CPM, linear scheduling, and bar charts for scheduling and monitoring transportation projects. The procedure is called repetitive activity scheduling procedure (RASP). RASP allows the use of linear scheduling approaches to plan and control linked repetitive operations where matched production rates are critical.

CURRENT PRACTICES

Several approaches have been reported for scheduling transportation projects. These range from simple bar chart to CPM networks and to some combinations of progress charts and linear scheduling techniques. A brief discussion of these techniques follows.

Bar Chart

The bar chart or Gantt chart has been used since the early 1900s. The bar chart plots activities versus time with the activities listed vertically. The major feature of a bar chart is that it is simple and easy to understand and clearly indicates when an activity will start and finish. The bar chart is preferred for scheduling field operations because superintendents, foremen, and craft workers can easily understand and apply it (3–5). Although representation of linear activities is possible in a network, the additional complexity has discouraged some use of this method. As a result, contractors often prefer the simplicity of a bar chart (2). However, the bar chart only relates given activities to a time scale. There is no indication of activity interdependence or identification of critical activities. The bar chart does not give the overall schedule impact should an activity be delayed. Bar charts are cumbersome to update; thus, they become nearly useless when the plan is not followed and changes occur.

Network Models

Network models, developed in the late 1950s and early 1960s, occur in one of two forms: as an activity on arrow (AOA) or an activity on node (AON) model. Both forms are CPMs. The CPM diagram illustrates the logical sequence of activities and shows the critical activities (i.e., those activities that cannot be delayed without delaying the project). Although the CPM has existed for more than 30 years, its application in transportation construction has been limited (3,6,7). There is evidence that contractors do not use networks in highly repetitive jobs (8). In transportation projects or projects consisting of repetitive activities, CPM requires the same activities to be repeated throughout the project's duration, resulting in a complex and cluttered network difficult to visualize. In addition, CPM does not guarantee the continuity of work and does not consider variable production rates. CPM's unrealistic assumptions of unlimited resources and independent activities that can be shifted freely between earliest start and latest finish creates a less-than-perfect model of reality that limits its use on linear and repetitive projects. This problem cannot be solved by resource allocation/leveling. Resource allocation, smoothing, or leveling procedures are incapable of ensuring full continuity for a production crew or process, which is the backbone of planning repetitive cases (6,9).

Linear Models

Because of the difficulties with CPM in linear construction, various forms of linear scheduling have been proposed as an alternative. The origin of the linear scheduling method is not clear. In fact, there may have been multiple origins, possibly in different countries (8). Linear models include a multitude of variations. What they have in common is that they are all used for planning and controlling highly repetitive projects. They have different names: line of balance (LOB), vertical production method (VPM), combined PERT/LOB, time space diagram, stochastic approaches, or linear programming. In several articles, the linear scheduling method and LOB have been described as synonymous. In fact, the linear scheduling method has some relationship to the LOB technique developed by the U.S. Navy in the early 1950s. The LOB technique was first applied in industrial manufacturing and production control to evaluate the flow rate of finished products in a production line (1). Any differentiation between linear scheduling and the LOB technique may only be a question of emphasis. In the usual application, the LOB technique is used to schedule or record the cumulative events of unit completion, whereas linear scheduling emphasizes planning or recording progress on multiple activities that are moving continuously in sequence along the length of a single project (2).

Although linear scheduling is used extensively in the Middle East (2), its use in the United States is very limited, and most of its applications to highway construction have been part of research or on a trial basis only (2,3,10). For example, in a survey involving more than 200 contractors working for the Illinois Department of Transportation, none used linear scheduling (8). There are major problems in the presentation of the information, and its success depends on the setting of production rates and more accurate estimates of work hours, because linear scheduling is sensitive to errors in these estimates (8).

Survey of Scheduling Methods Used by Various Departments of Transportation

A survey has been conducted to examine approaches used by various state departments of transportation across the United States to establish contract durations, control time on construction projects, and schedule resources for the annual construction program. The survey was sent to the chief construction engineer, or equivalent, for each of the 50 states and the District of Columbia. Responses were received from 36 of those surveyed. This paper includes the results of this survey and previous research on related subjects by Johnson (2), Herbsman (3), Thomas (5), and Rowings (11). Results of the survey are given in Table 1.

From the results of Table 1, the following observations can be made.

In response to the question of contract duration, 44 percent of states determine the project duration on the basis of personal experience and judgment or the best guess, depending on project type, size, and complexity; 30 percent use standard production rates; and 22 percent use past projects and historical records. Only 4 percent use CPM to establish contract duration.

Furthermore, contract duration is established at the state level by the vast majority of states (88 percent). Forty-seven percent of the states do not use a schedule specification, 27 percent use various scheduling specifications for different project categories, 20 percent use one specification on all projects, and 7 percent mentioned other unspecified methods.

In response to the questions on computer hardware and software, 53 percent indicated they did not use computers. Of those using computers, 56 percent use microcomputers, 22 percent use minicomputers, and 22 percent use mainframes. Primavera and Supertrack were the software used. In addition, 50 percent require their contractors to use the same software program.

TABLE 1 Survey of Scheduling Procedures for Highway Construction Projects

1. How do you determine contract durations?

[30%] Based on standard production rates [44%] Based on project type, size, complexity, etc.
[4%] Based on a CPM schedule [22%] Based on historical records (past projects)

2. Is the contract duration established at the state or district level?

[88%] State [12%] District

3. Do you include a standard scheduling specification in the construction bidding documents?

[20%] Use one scheduling specification on all projects
[27%] Use various scheduling specifications for different project categories
[47%] Do not use a standard scheduling specification
[7%] Other

4. Do you use any computer hardware for scheduling purposes and project management?

[53%] No [22%] Minicomputer
[47%] Yes (If yes, specify hardware) [22%] Mainframe
[56%] Microcomputer

5. What type of scheduling software do you use? Primavera; Supertrack.

6. Do you require contractors to use the same software as above?

[50%] Yes [25%] Left open to contractors subject to the state or district's approval
[25%] Not required

7. What scheduling method do you require of contractors?

[15%] None [35%] Bar Chart
[40%] Critical Path Method [0%] Line of Balance Method
[5%] Progress Curve Method [5%] Other: Narrative Report

8. Do you use CPM on all projects?

[0%] Yes on all projects
[53%] On selected project depending on size and complexity
[47%] No, we use Bar Chart or other methods on all projects

9. Do you require contractors to "cost-load" their schedules? [100%] No

10. Do you use cost/schedule integration? [80%] No [20%] Yes

11. Do you attempt to use contractor's schedules to develop a multi-project schedule for your own inspection and contract administration activities? [73%] No [27%] Yes

12. How frequently do you require schedule updates?

[0%] Biweekly [13%] Monthly [7%] Quarterly [13%] As required
[33%] Never [33%] Only when behind by 10 to 60 days or 20% of contract time

In response to what scheduling method is required of contractors, 40 percent indicated CPM, 35 percent bar chart, 5 percent narrative report, 5 percent progress curve, and 15 percent do not require any scheduling method. No one indicated use of LOB or linear scheduling techniques. As for CPM, 53 percent use it on selected projects, depending on size and complexity, whereas the rest use the bar chart. None of the states require their contractors to cost-load the schedules, and only 20 percent use cost/schedule integration.

In response to the question on multiproject schedules, 73 percent mentioned that they did not use contractor's schedules to develop multiproject schedules for inspection and contract administration activities. As for update frequency, 33 percent require schedule update when the project is behind 10 to 60 days or more than 20 percent of contract duration, 33 percent never update the schedule, 7 percent update the schedule quarterly, 13 percent update monthly, and 13 percent update only as required.

The results of this survey indicate some adoption of more sophisticated approaches for scheduling and control but not an overwhelming adoption of CPM or other approaches. Further information is being gathered from the respondents concerning their reasons for their choice of approach. A survey of highway contractors to gain similar information is also under way.

RASP

There may be several reasons why there has been reluctance to use linear scheduling on transportation projects. Although it is fairly easy to plan transportation projects using linear scheduling methods, in practice, there are several problems with scheduling such projects using this method. Linear scheduling techniques are based on the assumption that the rate of output will be uniform. Construction productivity, in practice, varies substantially from day to day even if the assumed average figures are correct. The schedule, therefore, has to be corrected to minimize the interferences that occur when activities are delayed by more than the buffer time allowed (*12*). Furthermore, transportation projects are not always as linear as they appear. For example, projects involving large cuts and fill are more difficult to schedule using linear scheduling than those in largely flat or gently rolling terrains (*2*). Earthwork activities do not necessarily move smoothly from station to station. Instead, an entire area is worked until subgrade is achieved.

Contractors prefer the bar chart because of its simplicity, high visibility, and ease of use. The user is directly involved, and the progress, even for complicated jobs, can be understood at a glance without the use of a computer and unaided by an elaborate scheduling approach. These features should be present in any schedule to be totally effective for updating and control. The fundamentals of project scheduling remain the same irrespective of the project size. A schedule is simply a road map of how its user intends to build the job within a given time frame. Therefore, the first objective of any type of project schedule is to communicate to its users and to reflect the planner's thoughts and intentions (*13*). RASP maintains the logic integrity of CPM, takes into considerations productivity fluctuations and activity interferences, and sustains the simplicity of the bar chart by combining all these features.

Project Type and Scope

The main conclusion of research conducted by Herbsman (*3*) is that transportation projects should be classified into four categories and that a different scheduling method be used for each category. The first category consists of simple projects less than $1 million in size and less than 6 months in duration. These projects will continue using detailed bar charts to plan and schedule the work. The second category consists of very complex projects, usually more than $5 million in size and more than 12 months in duration. These projects should use detailed CPM. This leaves us with two other categories of typical highway projects: those ranging from $1 to $5 million in size and 6 to 12 months in duration as well as any unique or special projects of various sizes and durations. For these projects, a combination of bar chart, CPM, and linear scheduling can be recommended. Bennet (*14*) identifies five characteristics of construction projects from a management view. He mentions that construction projects vary in size, complexity, repetition, speed, and variability in productivity. Different combinations and different values of these five characteristics provide significantly different management decisions (*14*). The variation in these characteristics is so large that one single scheduling technique cannot be applied to all types of transportation projects. Using Herbsman and Bennet's research as a guide, the scheduling method selection guide shown in Figure 1 was developed to identify the appropriate techniques for various project characteristics. These include size, complexity, repetition, timing, and variability. Depending on a number of these factors, or a combination, several recommended scheduling techniques are listed on the right-hand side of Figure 1. These range from simple lists and bar charts

PROJECT CHARACTERISTICS					RECOMMENDED SCHEDULING TECHNIQUE
SIZE	COMPLEXITY	REPETITION	TIMING	VARIABILITY	
<$1 M	SIMPLE/ STANDARD SINGLE STAGE SINGLE CONTRACTOR	SEMI-REPETITIVE PERFORMING A FEW FUNCTIONS A FEW TIMES	LOW SENSITIVITY SHORT DURATION <6 MONTHS FEW CRITICAL ITEMS NO IMPOSED MILESTONE DATES	NOT VARIABLE IN PRODUCTION SINGLE SEASON	[] SIMPLE LIST OF DATES [] SIMPLE BAR CHART [] BAR CHART BASED ON PROD. RATES [] PROGRESS CURVE METHOD [] COMBINED PROGRESS CURVE/BAR CHART
$1-5 M	TYPICAL HIGHWAY PROJECT	VERY REPETITIVE PERFORMING A FEW FUNCTIONS MANY TIMES	MEDIUM SENSITIVITY 6 - 12 MONTHS DUR. MANY ACTIVITIES CRITICAL OR NEAR CRITICAL	VERY VARIABLE IN PRODUCTION SEASON LONG LIMITED RESOURCES	[] REPETITIVE ACTIVITY SCHEDULING PROCEDURE (R A S P)
>$5 M	VERY COMPLEX MULTIPLE STAGES MULTI-CONTRACTORS HIGH TRAFFIC FLOW IN URBAN AREA	NON-REPETITIVE PERFORMING MANY FUNCTIONS A FEW TIMES OR MANY FUNCTIONS MANY TIMES	HIGHLY SENSITIVE LONG DURATIONS >12 MONTHS MOST ACTIVITIES CRITICAL	SEMI-VARIABLE IN PRODUCTION SEASON LONG LIMITED RESOURCES	[] TRADITIONAL CPM METHOD [] RASP/CPM COMBINED [] PERT OR OTHER SIMULATION METHODS

FIGURE 1 Project characteristics versus method used.

to more sophisticated techniques, such as progress curves and CPM, to using RASP.

Elements of RASP

The survey of various departments of transportation indicates that most agencies in the United States let the contractors decide what scheduling method to use and, in most cases, require only a simple bar chart. In some states, CPM is required only on selected projects. It is obvious that an alternative scheduling procedure is needed for projects to which neither the bar chart nor CPM is appropriate. Any alternative scheduling method must be simple, flexible, easy to learn, and adaptable to various contractors and field personnel. RASP can meet this requirement. Several basic elements are crucial for a working understanding of RASP.

Work Breakdown Structure

The first step in the development of RASP is to separate the project into the constituent component processes by establishing the project's work breakdown structure (WBS). The WBS is the separation of a project into smaller tasks, or work packages, to aid in organizing, defining, and displaying the project. It is a framework for integrating the schedule and resources that provides a means to define the scope of work required to meet the project objectives. Figure 2 is an example WBS for a roadway construction project. The project consists of replacing and upgrading a portion of a roadway with a new road between stations 10 + 00 and 70 + 00, approximately 1.09 mi. The roadway contains approximately 150,000 yd^3 of excavation, most of which occurs between stations 10 + 00 and 30 + 00. An 8- × 10-ft reinforced concrete box culvert must be built at station 47 + 00 before earthwork can proceed in that area. Traffic must be maintained on all existing roads throughout the project duration. Therefore, the work will be accomplished in phases with three sections (STA 10 + 00 to 30 + 00, 40 + 00 to 55 + 00, and 63 + 00 to 70 + 00) completed in the first phase. Work between Stations 30 + 00 to 40 + 00 and 55 + 00 to 63 + 00, where the new road intersects the existing road, will be completed in the second phase. During the second phase, the work will be performed one lane at a time to keep the other lane open to traffic.

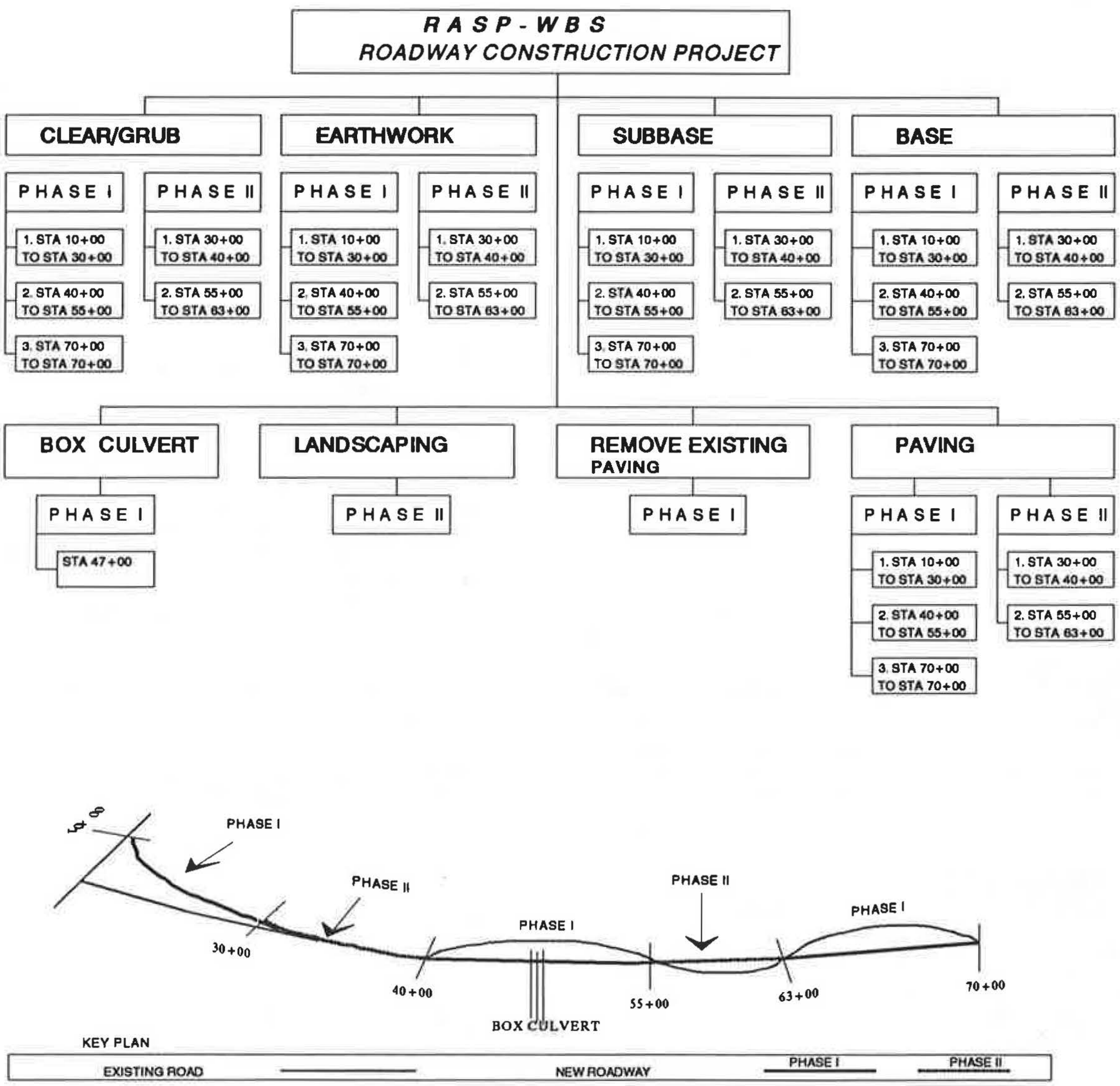

FIGURE 2 Example WBS for roadway construction project.

The WBS of Figure 2 shows eight major categories consisting of clear/grub, earthwork, box culvert, base, subbase, paving, pavement removal, and landscaping. These items are then further broken down by phases and those phases by phase. WBS levels are organized on the basis of the assumption that each group of activities is performed in a continuous production line.

RASP Worksheet

Figure 3 shows a sample RASP worksheet for Phase I of the example project. The worksheet is supplementary to the WBS and is essential to the development of the RASP schedule. All components of the WBS are listed in this worksheet. The RASP worksheet is used as an aid in calculating durations, planning resources, and identifying work stages and sequences. Contract time or contract duration has a major effect on the construction process. Severe time limitations placed on construction will result in high bidding prices and could lead to extensive claims (*11*). In repetitive types of work, duration is a function of crew sizes, equipment types, and production rates. CPM ignores these important factors when calculating durations (*9*). Using the RASP worksheet, the project planner considers all possible resources and how they are to be used, establishes daily production rates, and calculates durations on the basis of these factors. An attempt is made to capture most schedule assumptions and the planning thought process on this worksheet. Furthermore, this worksheet is used to report progress and calculate the percentage of work complete. This information, interfaced with the RASP schedule, can also provide progress curves based on the quantity of work and unit rates. As with the WBS, a key plan showing project location and work segments is shown for maximum visual impact.

RASP Schedule Format

The graphical display of the project plan showing activities, time, and location all framed in one picture is the heart of this technique. Therefore, size and format are prominent bases in the development of RASP. Figure 4 shows the RASP schedule for Phase I of the example project. The format consists of two sections both drawn on 8.5- × 11-in. paper. The top section resembles a simple bar chart and shows all the project's main components as identified by the WBS. The lower section is a plot of time (x-axis) versus distance (y-axis). Using

	CLEAR/GRUB			EARTHWORK			BOX CULVERT	SUBBASE			BASE			PAVING		
STATION -->	10+00-30+0	40+00-55+0	63+00-70+0	10+00-30	40+00-55	63+00-70+0	STA 47+00	10+00-30	40+00-55	63+00-70	10+00-30	40+00-55	63+00-70	10+00-30	40+00-55	63+00-70
QUANTITY	1	1	1.5	40000	24000	18000	100	5000	5000	5000	5000	5000	5000	5000	5000	5000
UNIT	ACRES	ACRES	ACRES	CYD	CYD	CYD	FEET	SQYDS	SQYDS	SQYDS	SQYDS	SQYDS	SQYDS	SQYDS	SQYDS	SQYDS
CONDITIONS AT SITE	LIGHT TREES	LIGHT TREES	ROCK	NORMAL		ROCK	8 X 9'REINF. CONCRETE									
EQUIPMENT:																
FRONT END LOADER	2	1	1	1	1	1	1									
BULLDOZER	2	1	1	1	1	1										
DUMP TRKS	3	1	1	2	2	2										
SCRAPER 16 CY				2	2	2										
PAVER																
ROLLER																
HYDR. EXCAVATOR				1	1	1	1									
MANPOWER:																
LABOR	7	7	7													
TEAMSTERS	3	1	1	2	2	2										
EQP OPER	4	2	2	6	6	6										
CARPENTER																
PAVER																
IRONWORKER																
PIPELAYER							3									
FINISHER														5	5	5
BUDGETED COST																
BUDGETED MANHRS																
DAILY PROD RATE	1	1	1.5	2000	2400	1200	5	1000	1000	1000	1000	1000	1000	5000	5000	5000
DURATION	5	5	5	20	10	15	20	5	5	5	5	5	5	1	1	1
SCHEDULED DATES																
TARGET START	WK 1	WK 2	WK 3	WK 2	WK 6	WK 9	WK 2	WK 6	WK 9	WK 12	WK 7	WK 10	WK 13	WK 14	WK 14	WK 14
TARGET FINISH	WK 1	WK 2	WK 3	WK 5	WK 8	WK 11	WK 6	WK 6	WK 9	WK 12	WK 7	WK 10	WK 13	WK 14	WK 14	WK 14
TOTAL FLOAT	0	0	5 WKS	1 WK	0	0	0	2 WKS	2 WKS	0	2 WKS	2 WKS	0	0	0	0
FCST START					WK 7	WK 10			WK 10	WK 13		WK 11	WK 14	WK 15	WK 15	WK 15
FCSAT FINISH					WK 9	WK 12	WK 7		WK 10	WK 13		WK 11	WK 14	WK 15	WK 15	WK 15
FCST FLOAT					-1	-1	-1		1 WK	-1		1 WK	-1	-1	-1	-1

PROGRESS UPDATE

ACTUAL QTY TODATE				40000												
% COMPL	100	100		100			75	100			100					
COST TODATE																
MANHOURS TODATE																
ACTUAL START DATE	WK 1	WK 2		WK 2			WK 3	WK 4			WK 5					
ACTUAL FINISH DATE	WK 2	WK 2		WK 5				WK 4			WK 5					

ASSUMPTIONS/REMARKS:

NARRATIVE REPORT

CONTRACT COMPLETION	TARGET	FORECST
PHASE I	WEEK 14	WEEK 15
PHASE II	WEEK 21	WEEK 21

PERCENT COMPLETE:
SCHEDULED (PER ORIG. PLAN) 31
EARNED (PHYSICAL % COMPL) 36
ACTUAL (ACTUAL $ EXPANDED) 35

COMPLETED ACTIVITIES:
CLEAR/GRUB STA. 10+00-30+00; 40+00-55+00
EARTHWORK TO STA. 30+00
SUBBASE/BASE TO STA. 30+00

ACTIVITIES BEHIND SCHEDULE:
BOX CULVERT 75% COMPL. 1WK LATE

ACTIVITIES AHEAD OF SCHEDULE
BASE TO STA. 30+00 1WK AHEAD

FIGURE 3 RASP worksheet.

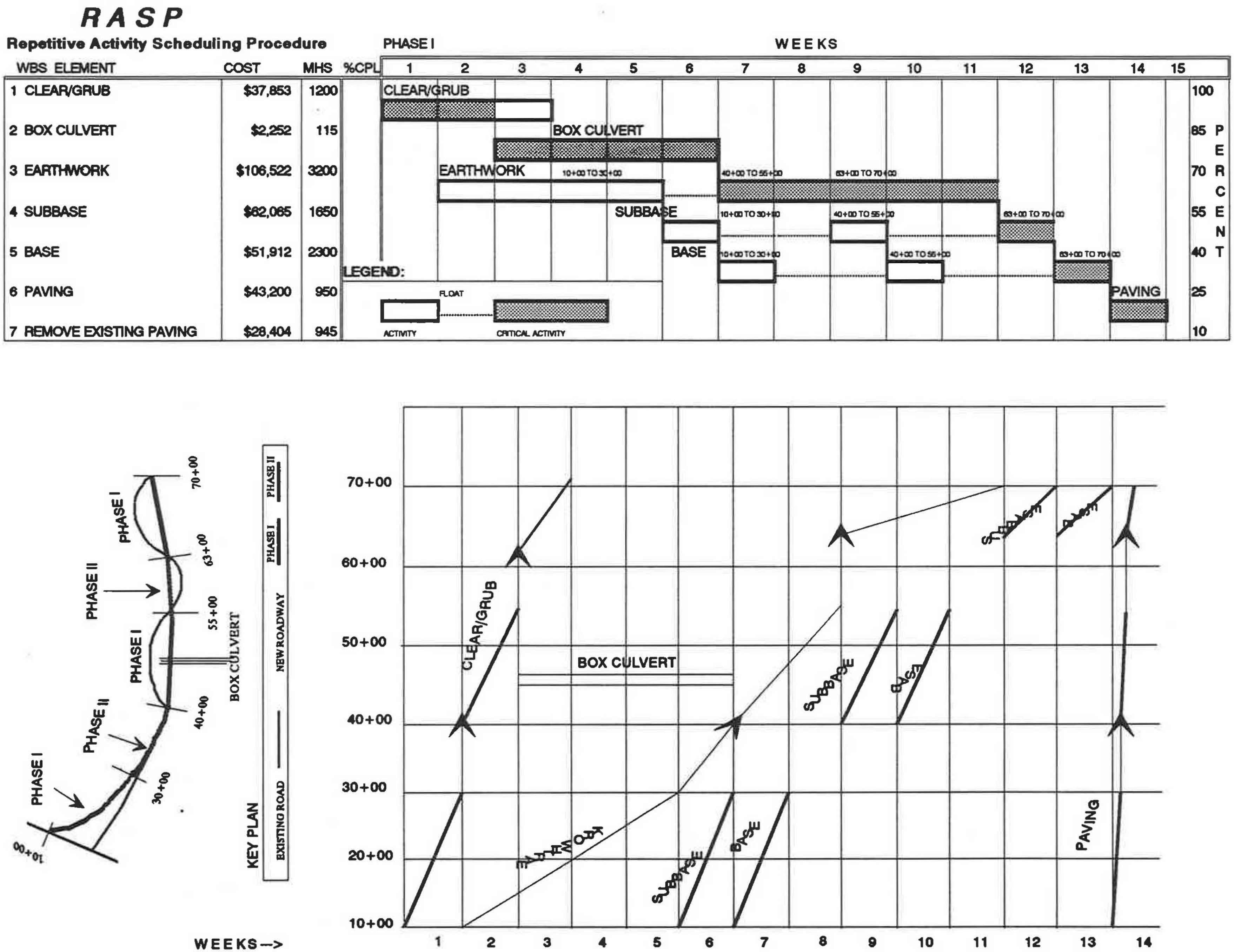

FIGURE 4 RASP schedule format.

the worksheet as a guide, the planner decides a starting place to begin the work. In this example, the work starts with clear/grub at Station 10 + 00. Clear/grub is then plotted on the lower section using the durations calculated on the worksheet. Each activity is a line whose slope and position are an indication of the planned work pace, productivity, and work area congestion. A vertical, dashed line indicates movement of a crew or resource from one section location to another, assuming there is no time loss in this movement. The arrowhead indicates the direction of the movement. A dashed line between activities expanding both vertically and horizontally indicates a delay in the start of the next activity. This may be due to a restraint, as indicated on earthwork between Sections 1 and 2. In this case, earthwork on Section 2 cannot start until the box culvert at STA 47 + 00 is completed. When there are no dashed lines between two identical items, float activity exists. Once the lower section is completed, the bar chart section can easily be drawn. The bar chart indicates the critical path as well as total and free float. Unlike the conventional CPM programs, with RASP the planner can see at all times where a project is headed. The planner can determine right away if the project can be done within a certain time frame. RASP is a flexible tool that guides the planner to be in control of the schedule.

CPM/RASP Combined

Although RASP can be developed without a CPM schedule, on more complex projects with substantial amounts of discrete activities it may be advantageous to develop RASP as a supplement to the CPM program. This can easily be accomplished with most software programs by downloading the semidiscrete or linear tasks and then performing the analysis using RASP.

Updating and Monitoring Progress

The ability to update a schedule in a few easy steps is one of the primary advantages of using RASP versus generic systems. This can be accomplished manually or by computer with minimal data entry compared with the time-consuming data reentry involved in generic systems. Figure 5 shows a RASP schedule updated through Week 6. The method in monitoring progress in RASP is similar to updating bar charts. On any specific date during the project, the working or calendar day can be marked with a line drawn vertically across the diagram. Progress on individual activities would be marked by location rather than time. Completed activities or activities in progress can be shaded, as shown in Figure 5. As long as the project is reasonably within the original or current target, there is no need to redraw the diagram. RASP is a dynamic scheduling tool that is quickly updated and can be more easily modified to reflect the project's changed conditions. The vertical status line provides the managers with a quick overview of the project's progress. When the project is significantly behind schedule or there are major revisions in the scope of work or operations, RASP will be revised and redrawn. Because of the simplicity of RASP, this rescheduling process is fairly easy.

Linear Scheduling and Progress Curves

According to the survey of scheduling procedures for highway construction projects, a number of agencies indicated the use of progress charts or progress curves. Progress charts display a two-dimensional representation of status and rate of progress (*15*). The horizontal axis shows time. The vertical axis can be used in a number of ways to show quantity, cost, or percentage of progress. Progress charts allow the managers to determine not only whether the project is ahead or behind schedule but also whether it is gaining or losing ground. Progress charts can easily be developed as a supplement of RASP. In fact, RASP and progress charts complement each other.

Since 1967, the U.S. Department of Defense and the Department of Energy have established what is known as the cost/schedule control systems criteria (C/SCSC) for control of selected federal projects. Although this system is primarily for use on large projects, certain useful features of this system may be applicable to transportation projects as well. The system, which uses the progress chart concept, consists of three major elements: budgets are time phased to provide a budgeted cost of work scheduled (BCWS); actual costs are captured as actual cost of work performed (ACWP); and the earned value concept is used to determine budgeted cost of work performed (BCWP). By a comparison of these three major elements, several conclusions about cost and schedule performance can be reached.

Earned value or achieved and accomplished value are terms used for determining overall percent completion of a combination of dissimilar work tasks or a complete project. Earned value techniques are applicable to both fixed and variable budgets, although there are differences in detail in applying these techniques. Performance against schedule is simply a comparison of what you planned to do against what you did, whereas performance against budget is measured by comparing what you did to what you have paid for. These ideas can be expressed as follows:

$$\text{Scheduled variance (SV)} = \text{BCWP} - \text{BCWS}$$

$$\text{Scheduled performance index (SPI)} = \text{BCWP/BCWS}$$

$$\text{Cost variance (CV)} = \text{BCWP} - \text{ACWP}$$

$$\text{Cost performance index (CPI)} = \text{BCWP/ACWP}$$

A positive variance and an index of 1.0 or greater is considered favorable performance. These calculations are used in determining forecast costs at completion.

Three basic methods are used:

- Method 1 assumes that work from this point forward will progress at planned rates whether or not these rates have prevailed to this point. This is expressed as

$$\text{EAC} = \text{ACWP} + \text{BAC} - \text{BCWP}$$

where

EAC = estimated at completion,
ACWP = actual cost of work performed to date,

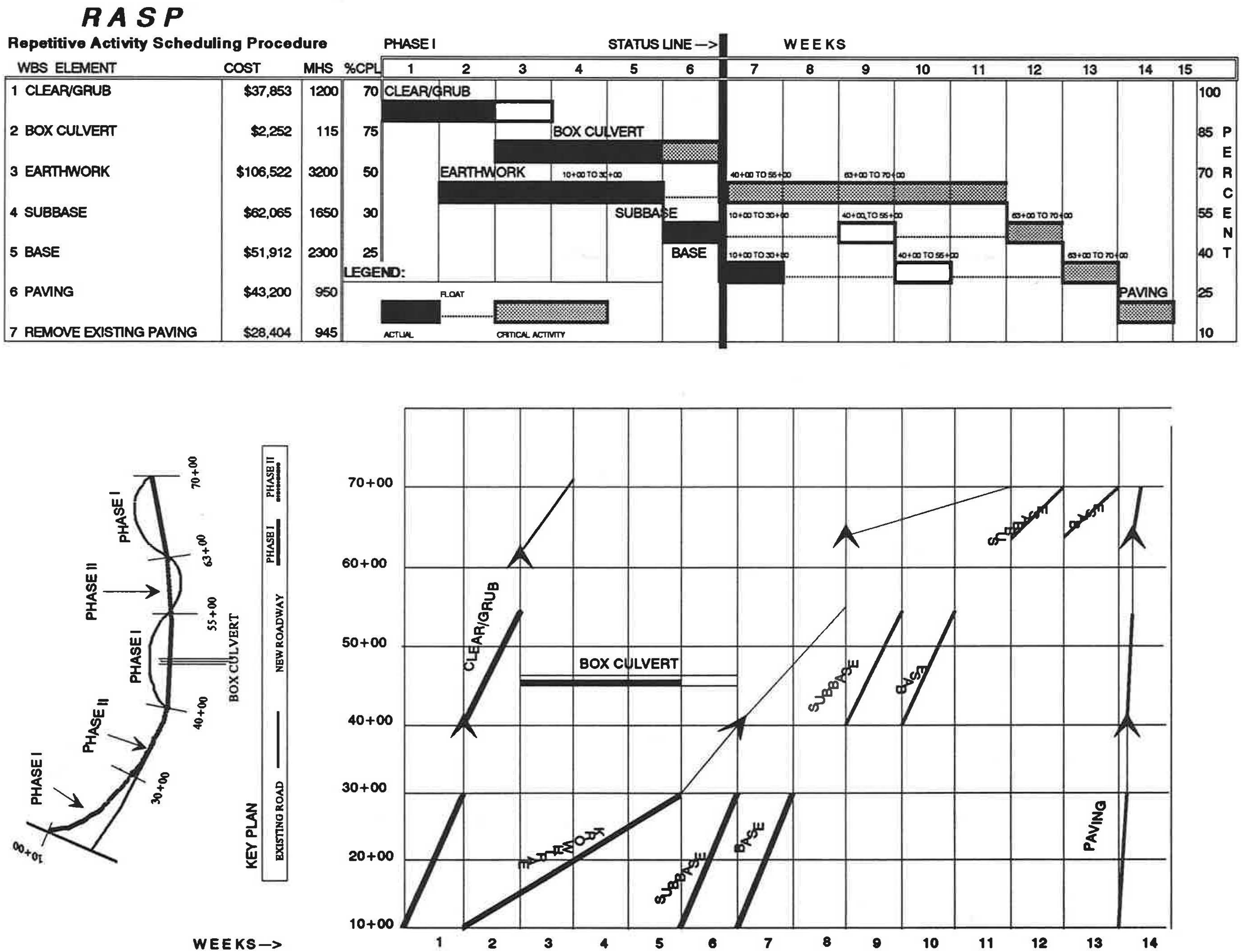

FIGURE 5 Updating RASP.

BAC = original budget at completion, and
BCWP = budgeted cost of work performed to date.

- Method 2 assumes that the rate of progress to date will continue to prevail and is expressed as

$$EAC = BAC/CPI = BAC * (ACWP/BCWP)$$

where CPI = cost performance index.

- Method 3 uses progress curves for forecasting as shown in Figure 6. Actual accomplishment—Point A—is plotted below the scheduled curve, indicating that the project is behind schedule. The actual amount can be determined by drawing or extending a horizontal line from Point A back to Point B on the schedule and measuring the schedule slippage. Likewise, the plotted cost—Point E—is located above the scheduled budget, but the amount of variation present in this parameter is not immediately apparent. The scheduled cost of the actual accomplishment must be determined rather than the cost listed for the current time frame. By extending a line vertically from Point B on the scheduled accomplishment until it meets the cumulative budget at Point C, we can determine what the cost for that accomplishment should have been. Continuing a horizontal line from there to Point D on the current time frame shows whether there is a cost overrun or underrun. In this case, the cost overrun is measured as the vertical difference between Points D and E.

It is recommended that no single forecasting method be used; rather, include a forecast by each of the preceding methods because they provide a range of possibilities.

Software Status

Although RASP can be developed without the use of a computer, it can easily be automated as required. RASP is an excellent candidate to be developed using spreadsheet programs combined with a graphics package. There are several commercial programs available from which to choose. Further research will provide guidelines for developing computerized RASP and its interface with other packages. In addition, RASP can easily be interfaced with CPM scheduling programs such as Primavera and others.

SUMMARY AND CONCLUSION

The scheduling approaches used today on transportation projects have many shortcomings for properly modeling the real world constraints and conditions that are encountered. A large number of projects exist whose characteristics dictate an approach different from the bar chart or CPM. An alternative approach, RASP, has been developed using the principles of the linear scheduling technique. The most obvious characteristic of RASP is its simplicity. The RASP schedule format and worksheet can easily convey detailed information that is comparable with what may be derived from an equivalent CPM schedule. RASP is a strategic planning tool that indicates the pace of work, allowing the planner to see how everything comes together and how the activities relate to each other. RASP provides an additional dimension not available with CPM or bar chart.

The technique requires a different form of data base than is currently kept to develop good estimates of production,

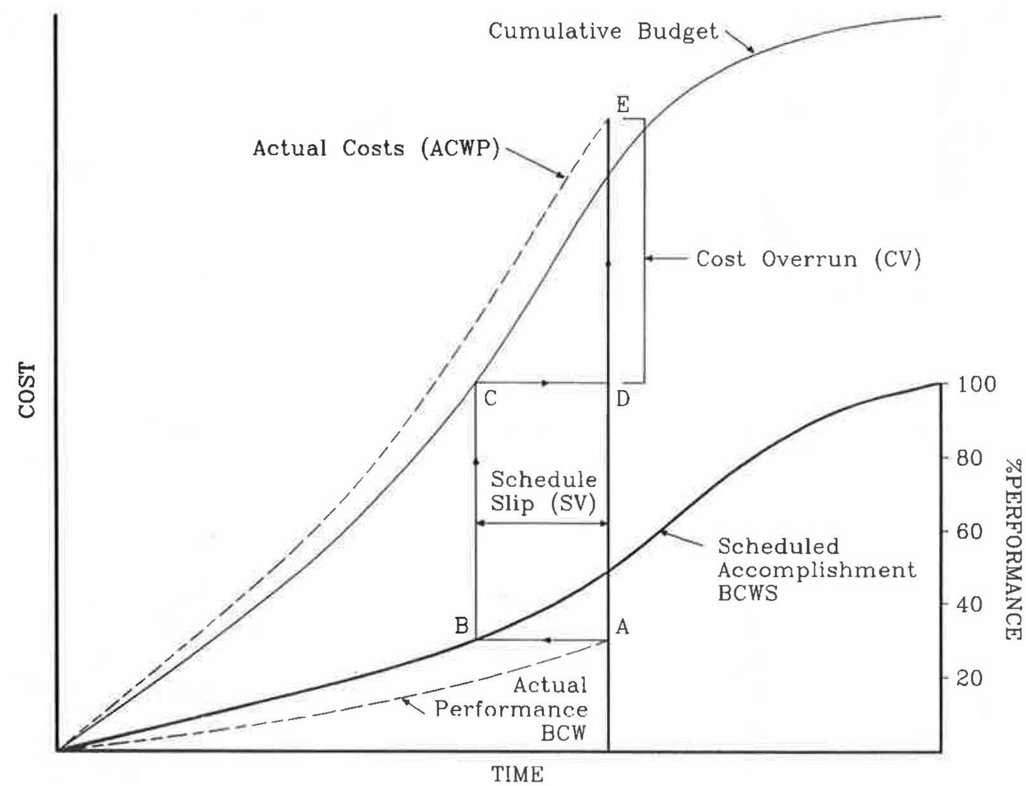

FIGURE 6 RASP and progress curve.

given certain resource combinations and working conditions. The system should offer an opportunity for improved planning and control of transportation projects.

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Linear Scheduling and Visualization

M. C. Vorster, Y. J. Beliveau, and T. Bafna

There has been a resurgence of interest in linear scheduling as a practical and visual tool for use in planning transportation construction projects. Network analysis techniques and bar charts do not provide the planner with an adequate means of analyzing the way in which crews move through time and space. Linear schedules can be used to overcome this problem. A review of linear scheduling research is presented to show the need for a standard format that combines the best of prior research and experience. Recommendations covering this format and the methodology to be used in a proposed standard format are presented. Three basic symbols—bars, lines, and blocks—are developed for use in drawing linear schedules. Some thoughts on specialized linear scheduling nomenclature are provided. It is concluded that the process of drawing bars, lines, and blocks on a linear schedule places the primary focus on planning and returns a measure of credibility to scheduling.

Major problems arise in the scheduling of transportation projects because of the flexibility available when planning the work. Projects such as highways, bridges, tunnels, and railroads have a significant linear dimension, and the work is therefore spread over a large area. Planning decisions as to where to start the project and how to pursue the work in an orderly fashion are extremely important because they are usually not subject to more than a few nonnegotiable technical constraints.

This flexibility in planning contrasts starkly with the heavily constrained situation that arises in building or other forms of vertical construction. Where to start and how to proceed is, by and large, dictated by the fact that foundations and the first floor come first and that subsequent floors follow in a given pattern with a limited amount of flexibility available in the macro-level planning process. The key to success on these projects lies in scheduling individual activities in a tightly constrained sequence. This contrasts strongly with linear construction, where the key to success lies in the planning needed to optimize flexibility in the use of space and time.

This paper shows how carefully designed linear schedules can be used as a tool in the planning that must precede the development of a realistic construction schedule. The focus is on a return to basics, and emphasis is placed on planning by visualizing the flow of processes that use time, space, and resources to produce quality construction on time and on budget.

IMPORTANCE OF VISUALIZATION

Most transportation construction projects are one-time and largely unique efforts of limited time and duration involving work of a nonstandardized and variable nature (*1*). Visualizing the flow of work through time and space is extremely important, and it is better to plan and replan than to produce a poor plan and experiment with it during project execution. The planner's ability to visualize the flow of work and a simple graphical tool to capture and record his or her thoughts make it possible to build and rebuild the project many times on paper. Field execution occurs only once, and neither time nor money is available to experiment with construction procedures that should have been optimized in the planning process.

Network analysis techniques and other mathematical approaches seldom allow or even require planners to have a complete feel for the project in the planning phase. Commercial software packages cause the planner to focus on providing the required inputs. Planning is seen as a rote, time-consuming process of dividing the work into a series of activities (less than 10 days long as required in many contract specifications), adding logic constraints and resource requirements, inputting the whole lot—via a spreadsheet list for increased efficiency—and seeing what comes out. Creativity in visualizing the flow of work and testing alternative strategic plans is smothered by the challenge of providing the input and understanding the output. Realism in planning is lost, scheduling becomes a farce, and execution proceeds according to the demands of the moment.

Bar charts have long been an effective tool for recording the planner's intentions on a time scale. The challenge of producing a well-drawn and detailed bar chart on a single, though large, piece of paper certainly causes the planner to visualize the flow of work and structure strategic alternatives with care.

The single dimension, time, presented on the x-axis of most bar charts reduces their effectiveness when the planner requires a clear vision of how work will flow from location to location. Linear schedules of the nature described in this paper overcome this limitation by providing a mechanism to show both the time and the location at which operations are to be performed. This allows the planner and, subsequently, users of the plan to develop a clear vision of what is to happen, when it is to happen, and where it is to happen.

LINEAR SCHEDULING TECHNIQUES

An awareness of the fact that the traditional network is not the best tool for the planning of linear projects and the shortcomings of bar charts in today's complex world has led to a resurgence of interest in techniques to assist in planning these projects (*2*). The techniques that have been developed are generally referred to as linear scheduling methods. Their origins are not clear, and there may have been multiple origins, pos-

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sibly in different countries. Many were originally devised to solve industrial production problems, and their use in the construction industry is a rather recent event. The techniques include a multitude of variations and a variety of acronyms (*3*).

Projects that are generally characterized as linear may be divided into two categories. The first includes projects that are linear due to the uniform repetition of a unit network of activities throughout the project. Multiple housing projects involving the repetitive construction of similar houses are a good example of this category. The second category includes projects that are linear essentially due to their physical layout. Highway projects, tunnels, railroads, and many transportation projects are excellent examples of this category. These projects are generally not characterized by the uniform repetition of a unit network, and they involve a number of activities that are discrete or unique in nature. The distinction between repetitively linear and physically linear projects provides a good basis for classifying the techniques, which have been used with varying degrees of success in the construction industry.

Techniques for Projects Characterized by the Repetitive Use of a Unit Network

Construction activities on linear projects are similar to the continuous manufacture of many units on a production line. The development of a prototypical unit network is helpful for these projects. Some techniques such as line-of-balance (LOB) scheduling and the vertical production method (VPM) use the concept of a unit network to graphically depict the construction schedule.

LOB

The LOB technique was developed by the U.S. Navy Special Projects Office in the early 1950s (*4*). It was first applied to industrial manufacturing and production control, where the objective is to attain or evaluate a production line flow rate of finished products (*5*). LOB has proven itself an effective management tool for steady-state production activities (*6*).

The LOB technique requires the following three inputs (*7*), which are usually represented graphically: (*a*) a unit network (production diagram) showing activity dependencies and time required between activity and unit completion, (*b*) an objective chart showing cumulative calendar schedule of unit completion, and (*c*) a progress chart showing the completion of the activities for each unit.

Al Sarraj (*8*) "formalized" the LOB method by developing its algorithms. He states, "By adopting the method in its formalized form, there is no need for any diagrams to be drawn as a means of defining the schedules." This approach, though mathematically and technically elegant, is counter to many of the arguments made in favor of graphical presentation to assist in visualizing the flow of work. LOB has been used in some linear construction projects characterized by the repetitive use of a unit network (*3,7,9*). Its widespread use on all types of linear projects is, however, doubtful because there are many factors inhibiting representation of the entire project by repetition of a unit network throughout the duration of the project. Kavanagh (*10*) states that LOB techniques "were designed to model simple repetitive production processes and, therefore, they do not transplant readily into the complex and capricious construction environment."

Ashley (*11*) comments on the usefulness of LOB in complex linear construction projects and states that "Learning curve effects, 'come back' delays, constraining resources, and stochastic activity durations, all important characteristics of repetitive-unit construction cannot be modeled by the LOB technique."

VPM

VPM was developed by O'Brien (*12*) specifically for use in construction of high-rise buildings. O'Brien recognized the importance of using a network to schedule basic preparation work such as site work, foundations, and structures to the first typical floor. He pointed out that the whole project momentum changed with the construction of the first typical floor and that, from this point onward, the work could be presented by a unit network for a typical floor.

The diagram that O'Brien (*12*) and O'Brien et al. (*13*) used to graphically portray VPM is, in many ways, similar to the linear scheduling diagram discussed in the next section. The horizontal and vertical axes are used to depict time and floors, respectively, in the high-rise building.

Techniques for Projects Characterized by a Linear Physical Layout

Some construction projects are linear essentially due to their geometrical or physical layout. They are not characterized by uniform repetition of a unit network and generally involve a number of activities that are discrete in nature. The execution of the linear activities is often not in a uniform fashion from the start to the end of the project.

Graphical techniques such as the linear scheduling method and the time-space scheduling method have been successfully used to plan and schedule projects of this type. Gorman (*14*) was among the first authors to suggest the use of a "time versus distance diagram" to achieve better communication of schedule information through visual impact in rapid transit, highway, and pipeline projects. This diagram had location on the *x*-axis and time on the *y*-axis. Clough and Sears (*1*) adopted essentially the same format when presenting "a bar chart for repetitive operations" in their book. The example used shows repetitive activities for a pipeline relocation drawn as straight lines on a graphical layout.

Johnston (*5*) first used the term "linear schedule method" in a research paper that focused on highway construction. He discussed the basic elements and concepts of the linear schedule method and used the *x*-axis to measure time. The *y*-axis plotted location along the length of the project. Activities were plotted as a series of diagonal lines with linear productions rates used to define the slope of the lines. Barrie and Paulson (*15*) present an essentially similar diagram as a "linear balance chart" but also present a "horse blanket schedule" based on schedules used on the Washington, D.C., and Atlanta, Georgia, rapid transit projects. This schedule showed distance on the x-axis and time progressing upwards on the y-axis.

Chrzanowski and Johnston (*16*) provided an excellent example of linear scheduling applied to a highway project in North Carolina. They show the survey stations along the project plotted on the x-axis with time progressing downward on the y-axis.

Vorster and Parvin (*17*) adopted an approach essentially similar to that of Barrie and Paulson to develop a linear scheduling format for highway construction. This format has a strong visual impact and an intuitive linkage to the highway construction process:

1. The x-axis or horizontal dimension of the linear schedule is used to measure distance along the project in a manner consistent with the actual physical layout of the works.
2. The y-axis or vertical dimension of the schedule diagram is used to measure time. Early dates are placed at the bottom so that early operations such as clearing are drawn below later operations such as surfacing to provide an intuitive linkage with the layered sequence in which field operations actually occur.
3. A set of three simple graphical symbols (bars, lines, and blocks) are used to show the way in which the planner has provided time and space for each of the logically sequenced operations.

Bafna (*18*) expanded on this work to develop what will, it is hoped, become a standard format for linear scheduling on transportation-type construction projects that have a significant linear or distance dimension.

A STANDARD FORMAT AND SYMBOL FOR LINEAR SCHEDULES

Strong arguments have been put forward to support the notion that successful planning can only be achieved if the planner is able to clearly visualize the flow of work and resources needed to complete a given project. Linear scheduling has been proposed as a simple graphical tool that can be used to capture the planner's thoughts. Research to date has been reviewed to arrive at a format optimizing the visual impact of linear schedules when used on transportation construction projects.

The proposed format for linear scheduling is described in the hope that this will lead toward a measure of standardization. The methodology proposed is simple but will add to a better understanding of the technique and the results obtained.

An example will be used to describe the concepts discussed. The project is 10,000 ft long (Station 0 to Station 100). The start date is August 1, 1991, and the end date is April 1, 1992. The work includes a retaining wall between Stations 15 and 25, a bridge at Station 65, and a number of regular grading and paving operations.

Allocation of Axes

The clear distinction between LOB and linear scheduling showed that in most, if not all, linear schedules the horizontal (x-) axis is used to depict distance or location along the project. This is logical because it creates a strong intuitive and visual link between the work and the diagram that displays the intended plan or action.

Time is allocated to the vertical (y-) axis with early dates placed at the lower end of the scale. This further reinforces the intuitive and visual linkage between the work and the linear scheduling diagram in that early operations such as clearings, drainage structure construction, and grading appear below the later, and, in a physical sense, upper operations such as subbase, base, and surfacing.

The selection of scales and labels for use on the axes depends on the level of detail desired in the diagram. Division by station on the x-axis and by month on the y-axis is commonly used. Major and minor labels are used to mark the axes and scale points. Figure 1 shows the allocation of axes and labels for the example.

Graphical Details

Details regarding location and time aspects can and should be added to the linear scheduling diagram at the onset. They remind the planner of the physical aspects of the work and ensure that the planning process takes place within a proper framework.

Plans

At times it will be advantageous to add a rough project plan to the top of the linear schedule to show information regarding the location of ground features such as access points intersections, crossovers, bridges, and culverts. The plan should be drawn to the same scale as the horizontal axis and be approximately aligned with it. Figure 2 shows the addition of the project plan to the top of the schedule being developed for the example project. It clearly shows the location of the retaining wall, which spans from Stations 15 to 25, and the bridge at Station 65.

Profiles

It can be advantageous to add a profile of the project at the top of the scheduling diagram. This profile should be drawn

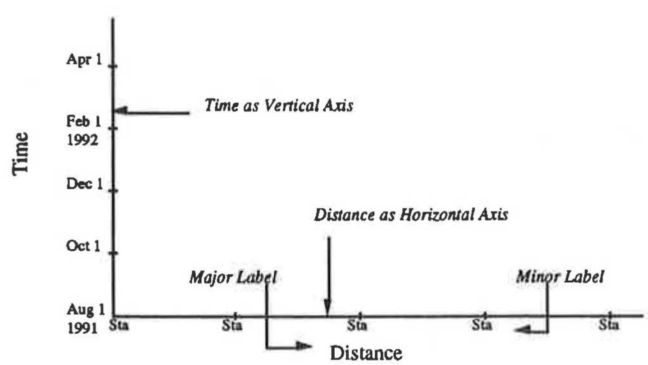

FIGURE 1 Allocation of axes and labels.

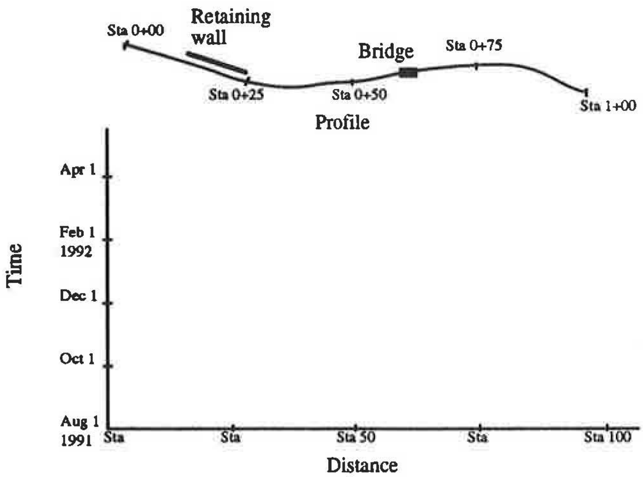

FIGURE 2 Addition of a rough plan to the linear schedule.

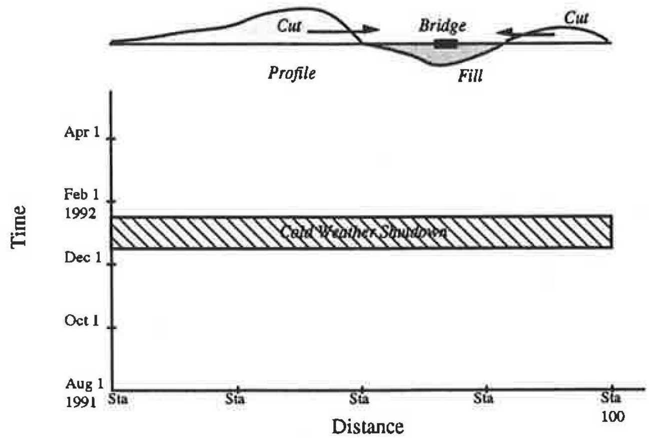

FIGURE 4 Season constraints.

with the same horizontal scale as used for the distance axis and should be aligned with it. The profile should show such features as cuts and fills, drainage structures, bridges, and other points of interest. The profile helps in visualizing the earthwork operations because the cut and fill locations are easily seen. A profile for the example project is shown in Figure 3. The profile shows cuts from Stations 0 to 50 and 80 to 100 and a fill from Stations 50 to 80. The addition of arrows helps in identifying the flow of material.

Season Constraints

Construction projects frequently depend on seasons, since almost all the construction work is executed outdoors. It is therefore advantageous to mark on the linear schedule the time periods when the work cannot be carried out because of bad weather. Figure 4 shows how an extreme cold weather period from December 15, 1991, to January 15, 1992, can be represented to remind the planner that this period is not available for work.

Access Constraints

There are situations in the field when access to the entire project is not simultaneously available to the contractor. Marking the access profile on the linear schedule will serve as a constant reminder of the unavailability of sections of the project and will help in planning operations accordingly. Figure 5 shows that the section between Stations 75 and 100 of the example project will not be available for 2 months from the project start date.

Sight Lines

Addition of vertical and horizontal sight lines to the scheduling diagram makes determination of the start and end dates and start and end station of an activity easier. Sight lines can be conveniently spaced on both the axes according to the required level of detail. Figure 6 shows the addition of sight lines to the example. Horizontal sight lines are placed at every second month and vertical sight lines after every 25 stations.

Sight lines may be added at dates or sections of special significance. A horizontal line is frequently used to mark the end date, and special vertical lines can be added at the end

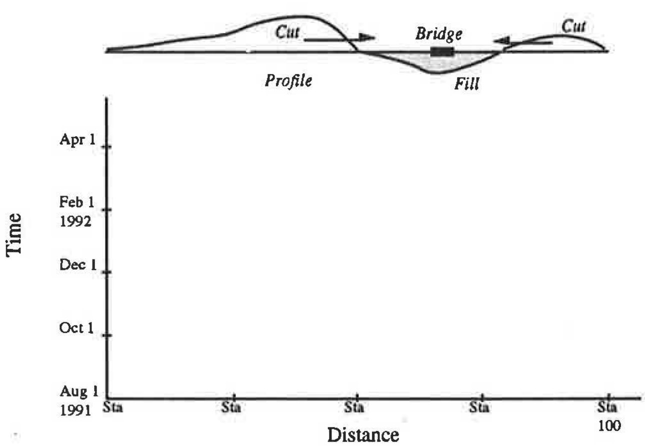

FIGURE 3 Addition of a profile to the linear schedule.

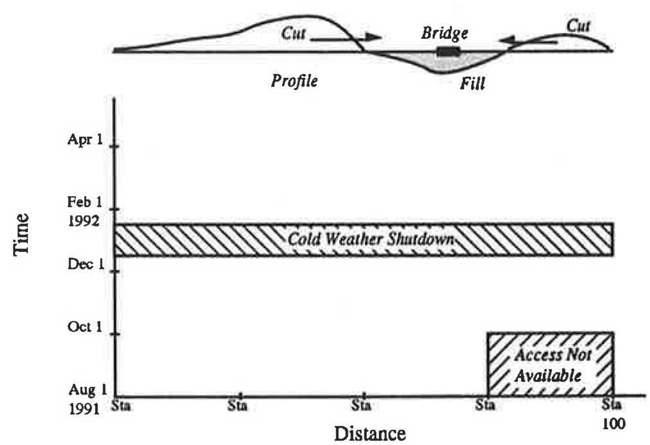

FIGURE 5 Access constraints.

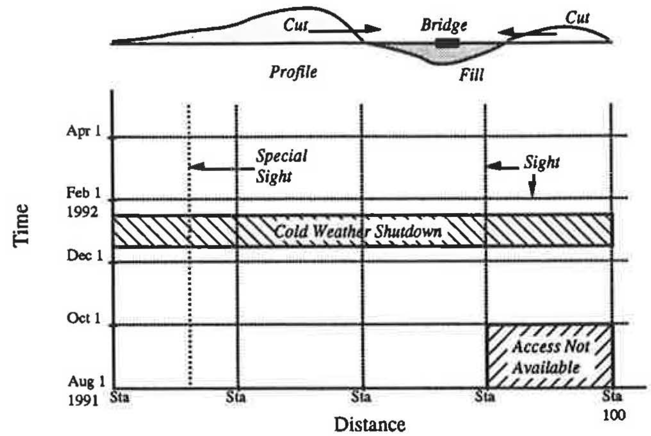

FIGURE 6 Sight lines.

of a significant section of the project. Figure 6 shows a vertical line drawn at Station 15, which, in conjunction with the regular sight line at Station 25, marks the start and end of the retaining wall.

Standard Symbols

The axes, graphical details, and sight lines provide a structure to the arena within which the planning must take place. Three relatively simple symbols geared to the nature of the work being planned can be used by the planner to depict the flow and interrelationships of the work.

Bars

Some operations, such as bridge or culvert construction, require that work be performed at a given location for a relatively long period of time. These operations are best represented by bars defined by the location of the work and the time needed to complete the tasks represented. Figure 7 shows a bar with location appropriately placed on the distance scale and start date, end date, and duration appropriately placed on the time scale.

Lines

Lines are drawn to track the movement of a crew or a particular operation through the job as time progresses. Operations such as the various base course layers surfacing or track laying can be effectively represented by lines because the work moves ahead at a relatively steady rate. The slope of the line represents the rate of progress; a flat slope represents substantial progress in a given period, and a steep slope represents little progress over time. Figure 8 shows the use of a line to represent operations on a linear schedule. The line from A to B has a steeper slope than the line from B to C to show a slower rate of progress.

Blocks

Blocks are used to represent operations that do not move smoothly from location to location. The crews thus occupy a substantial portion of space for a given period of time. Grading operations of various types are well represented by blocks because it is not possible to pinpoint the location at which work will take place at a given time. Other symbols, such as bars or lines, may fall within a block representing another activity, but care must be taken to ensure that the tasks depicted do not compete for the same space at the same point in time.

Figure 9 shows how a block may be used to represent the time and space needed to perform the work lying between A and B on the distance scale.

Additional Graphical Conventions

Linear scheduling is a planning tool designed to capture the thought processes of the planner seeking to optimize the use of time and space. The standard format and symbols described in this section provide a starting point for the creative thought needed to develop and document the plan of operations for a major project. Discussion of all the possible techniques, symbols, and styles used to draw a linear schedule within the framework presented here is clearly beyond the scope of this

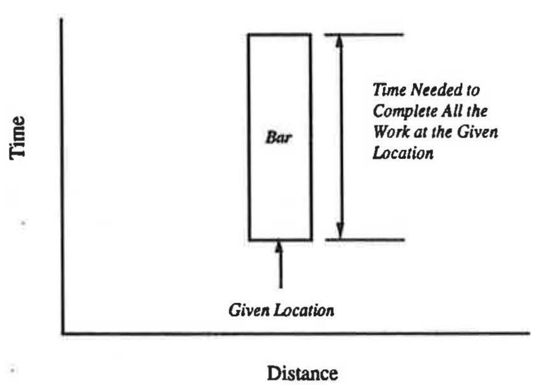

FIGURE 7 Bar used to represent operations on a linear schedule.

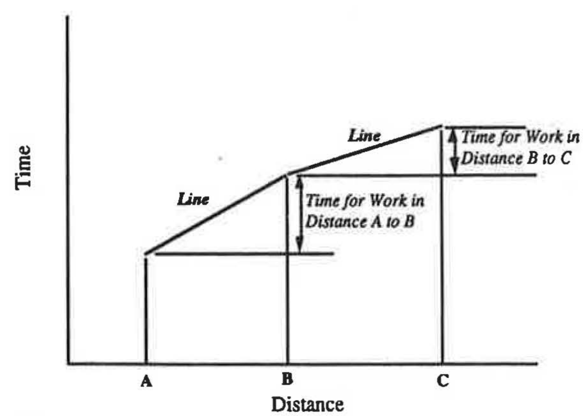

FIGURE 8 Lines used to represent operations on a linear schedule.

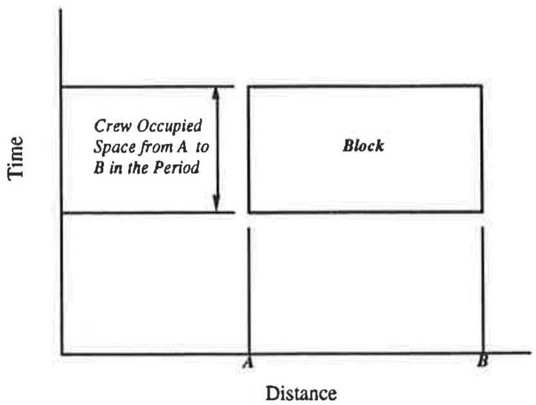

FIGURE 9 Block used to represent operations on a linear schedule.

paper. Every planner uses his or her own imagination to present a solution to a given problem.

Three examples will be given:

1. Colors, fill patterns, and line types: The visual impact of the schedule and the ability to trace the flow of crews and work can be greatly enhanced by the use of different colors, fill patterns, and line types. Figure 10 shows the visual input and clarity available by using fill patterns and line types.

2. Special symbols for earth movement: The judicious use of figures, arrows, and notes can modify the blocks used to depict grading operations to the extent that they replicate a standard grading diagram. The use of these special symbols is shown in Figure 11. Incorporating these can bring to life the intent of the overall earth-moving operation.

3. Multiple adjacent schedules: A number of schedules can be drawn side by side to the same time scale to depict nonlinear sections of the same project or show how crews move from one project to another in a multiple-project situation. Figure 12 shows how the two project components can have the same time scale with different locations. This side-by-side look can provide an overall feasible plan for moving crews from one location to another.

CONCLUSIONS

Figure 13 shows the planning depth that can be achieved using linear scheduling. A bar chart or CPM schedule cannot provide the same level of understanding as a visual schedule. What-if scenarios can be played out to determine options and reduce overall project time. Only when these visual tools are used will linear transportation projects take on a meaning that is readily transferable among all members of the site and office.

Success in the execution of transportation construction projects demands that work be done in an ordered sequence, that production crews be given the time and space needed to perform, and that delays and changes be minimized. The foundation for success in these areas is laid in the planning process, and the planner must visualize how the space provided by the physical dimensions of the project can be used to achieve a desirable construction sequence. Neither networks nor bar charts are of much value in this regard as they cannot represent space and time in a visual and easily understood format.

There has been a resurgence of interest in linear scheduling as a tool to help the planner capture thoughts and commit them to paper. The standard format proposed earlier is a product of this resurgence, and a number of complex projects have been planned using the techniques described. The process of drawing bars, lines, and blocks to depict the movement of crews and the interrelationships between activities placed the primary focus on planning rather than simply scheduling these projects and returned a measure of credibility to the resulting project schedules.

Much work needs to be done. Prototype software to integrate linear schedules and networks has been developed and is under test. The software combines the powerful ability of network-based techniques to calculate dates with the best visual and spacial attributes of the linear schedule. The ob-

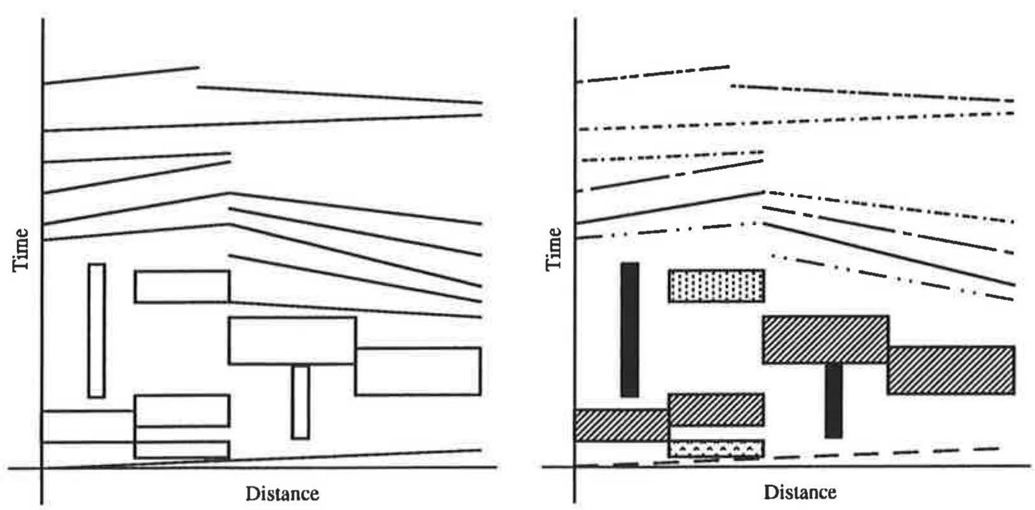

FIGURE 10 Example using fill patterns and line types.

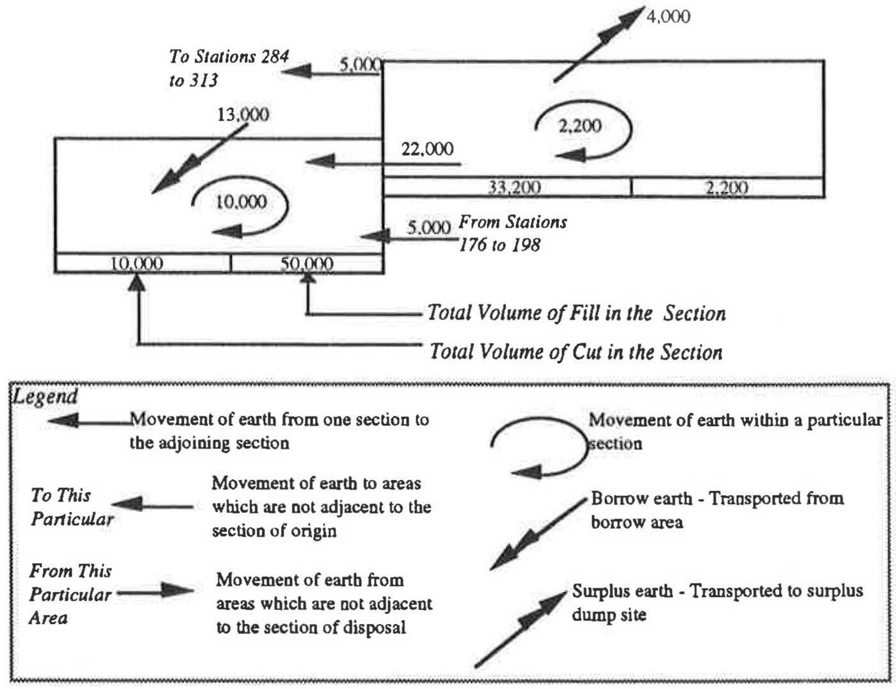

FIGURE 11 Special symbols for earth movement.

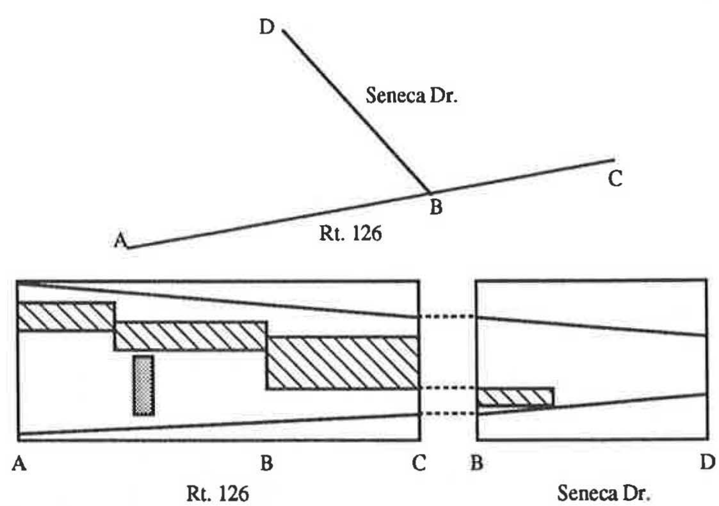

FIGURE 12 Multiple adjacent schedules.

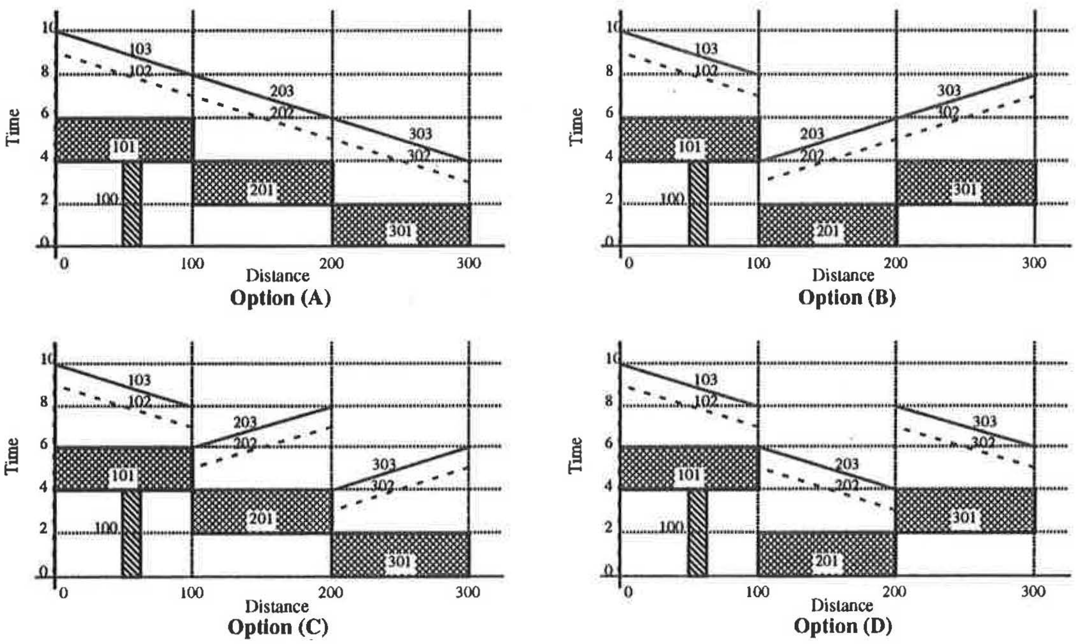

FIGURE 13 Linear scheduling as a graphical simulation tool.

jective is to produce a document incorporating the rigor of network analysis in a clear, intuitive visual display of the planning intent.

Implementation and development of the techniques presented in this paper are progressing. The results obtained to date have been of benefit to both owners and contractors.

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Scheduling Linear Projects Using Ranked Positional Weights

V. K. Handa, P. W. M. Tam, and A. Kwartin

Construction projects are commonly scheduled using the critical path method with the assumption that resource provision is not restricted (i.e., no machine breakdown is assumed and there is no problem with labor supply). An easier method, called the positional weight method, for both unlimited and limited resources is presented. There is no need to determine the critical path, and hence the problems associated with determining total floats, slack time, and the like are no longer present. The method has been applied for scheduling assembly line manufacturing. Because there are similarities between assembly line manufacturing and construction projects, especially linear projects, the method can be applied to construction.

The conventional method for scheduling a construction project is to draw a network diagram for the activities and obtain the shortest duration using the critical path method (CPM). Scheduling of the works is then based on the critical path. The CPM method for scheduling is well established and is widely used in the construction industry. For easier application of the technique, various software, including Primavara and Timberline, are available. The positional weight technique is very much used for scheduling assembly lines in the manufacturing industry. There is much similarity between assembly line manufacturing and linear projects in the construction industry. Using the positional weight (which is the sum of the activity and all subsequent activity durations), the activities are assigned in accordance with the relative "heaviness" of the activities. To assist in the application of the method, a computer program has been written in GW-BASIC.

LINEAR PROJECTS

Many transportation projects (for example, highway tunnels) are linear in nature. In the construction of a highway tunnel, rock excavation is to proceed first. Subsequently, the walls of the tunnels are temporarily stabilized, and then the precast rings are installed or in situ concrete placed to form the permanent support for the excavated face. Laying of surfaces is usually done before the installation of the permanent support system. Construction of road pavement then proceeds, and finally, signaling, communication, lighting, and ventilation systems are installed. All these construction activities are linear in the sense that they all proceed in one direction. Such construction activity is also repetitive in nature. As in the case of tunnel construction, it is unlikely that excavation can be done in one operation (except for very short tunnels). Otherwise, the unsupported length will be too long and tunnel collapse will be imminent. Even if temporary supports are provided, they will deteriorate and be rendered useless. More often the practical solution is to excavate a reasonable length by tunnel boring machine (TBM) or by drill and blast operation. The unsupported length often depends on the ground and groundwater regime. The excavated face is then protected by shotcrete/sprayed concrete. All the other work mentioned previously can then proceed sequentially. The whole operation is repeated for the next tunnel length. This process continues until the tunnel is complete. There is a need in this construction to determine the number of people and the types and number of machines that are required for each stage of the work. For example, what kind of TBM is to be used, and how many people and how many shifts are required to produce a reasonable length within a reasonable time frame? It is also necessary to determine how many spray concretors are required to provide the temporary protection. This process is repeated for all subsequent activities. Similar operations occur in other transportation projects—bridge, road, and railway line construction.

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ASSEMBLY LINE MANUFACTURING

In assembly line manufacturing, workstations are assigned on a line. Assemblers or machines or robots at various workstations work on the line sequentially. A product is produced after it has been assembled from the first station until the last station.

RANKED POSITIONAL WEIGHT TECHNIQUE

One method, known as the ranked positional weight technique reported by Helgeson and Bernie (*1*), is used in assembly line balancing. Each work element is assigned a weight, which defines its position relative to the others in a descending order. The positional weight is the sum of the operating time required for that element and the times for all elements that must succeed that element. The elements are ranked in descending order in accordance with their positional weights. Once a desired production rate is determined, the cycle time can be calculated. This is the reciprocal of the production rate. The production rate is defined as the number of complete units produced over a period of time. The work elements are then assigned to workstations starting from the highest positional weight, subject to any precedence logic constraints. This means that a proper order must be followed for assembling the work elements. Work element assignment is carried out in such a manner that the cycle time is not exceeded by any workstation.

In addition to precedence constraints, there are technological and zoning constraints. Because of the specialized nature of certain work elements, it is necessary to assign them to particular workstations. This reflects the technological constraint. Because of interferences between work elements, it is desirable to separate the work elements on different workstations. This restriction is known as the zoning constraint.

TRADITIONAL METHOD OF RESOURCE LEVELING

In a traditional method of resource leveling, activities are assumed to be able to start as soon as possible in accordance with the precedence network. It is necessary to determine the critical path first. All activities that are not on the critical path have a certain degree of float, and it is possible to schedule them to begin at some later date. This permits noncritical activities to start at more convenient times, when the demands for resources are reduced. This process is known as resource scheduling.

To obtain an optimal solution to the scheduling problem, one has to resort to the techniques of operations research, such as linear programming and integer programming, among others. To schedule a construction project with hundreds of activities, high-speed computers with high memory storage capacity are required. Computing costs for solving such large problems are large. Instead of trying to obtain an optimal solution, some rules have been designed so that a close-to-optimal solution can be found while bypassing the computational difficulties. A set of these rules is called a heuristic.

There are many sets of heuristic rules. Some aim at minimizing the duration, and hence the cost and availability of the resource are of no consequence. Others minimize the duration of the project while restricting the level of resources. The first method is called unconstrained resource scheduling (URS), and the second is constrained resource scheduling (CRS).

Harris (*2*) describes the minimum moment algorithm, which is intended to consolidate various other heuristic methods into a workable method. It is a URS method, and thus the project duration is maintained. The argument for this approach is that in a construction project, the project duration is usually fixed, and only after the contract is awarded is the project manager faced with the problem of resource scheduling to reduce the manpower and machine requirements.

The method is based on a precedence network. It is assumed that activities cannot be split and that the resource rates are continuous throughout the duration of the activity. This algorithm uses an early start schedule derived from the CPM.

SIMILARITIES BETWEEN RESOURCE LEVELING AND ASSEMBLY LINE BALANCING

In resource leveling, the resource level for a particular activity is the number of workers required for the activity each day over the duration of the entire activity. In assembly line balancing, the operating time on each element is also a "resource" in the sense that it is a time assigned to the work element. From this approach, it can be seen that a work element is similar to an activity in resource scheduling because it requires resources.

A workstation in assembly line balancing is a fixed location where work elements are grouped together to be worked by an assembler. In construction, a project day also has a fixed location on a project time calendar where resources are required to perform the activity. A workstation is therefore similar to a project day.

In a construction project, certain activities may span several days. However, in assembly line balancing, it is not feasible for several workstations to be assigned to an assembler or work element simultaneously. This is the basic difference between the two processes. A work element in assembly line balancing occurs at only one station, but in resource scheduling, an activity may span several days.

In assembly line manufacturing (ALM), to avoid idling time in different workstations it is desirable to complete the portion of work in the same amount of time as other stations. In this way, there is no need for one station to wait for the other just because one station finishes the work much faster than the preceding station. To optimize resource allocation, it is necessary to assign different contents of work to each station so that all stations complete the work at the same rate as others. The overall production rate is the number of products produced over the time from the first workstation to the last.

In CRS of a construction project, the idea is to minimize the project duration and to allocate resources within the constraints.

In ALM, the cycle time (i.e., the time required for all workstations to complete the assembly work) is more or less constant. No workstation can exceed the cycle time. In CRS, a maximum amount of resources can be assigned on one day and may not be exceeded.

The required cycle time depends on the workstation with the longest operating time. This means that the cycle time cannot be less than the longest working time in any particular station. Because it is not always possible to maintain the same operating time for all stations, the best policy is to reduce the idling time by rearranging work contents in each station such that the operating time is about the same for all stations. As such in construction, the cycle time is equal to the maximum resource per unit time.

Kwartin (*3*) compared assembly line balancing and resource scheduling (see Table 1).

APPLICATION OF THE POSITIONAL WEIGHT METHOD TO LINEAR PROJECTS

Before the method is discussed, it is necessary to define "positional weight." The positional weight of an activity is defined as the sum of the duration of all succeeding activities. This is illustrated by considering an activity in the example project. Details of the project will be discussed later. In Figure 1, it can be seen that Activity 31 is followed by Activities 33, 34, 35, 36, 37, 38, and 39. The positional weight of the activity is equal to the duration of the activity itself plus the duration

TABLE 1 Comparison Between Assembly Line Balancing and Resource Scheduling (3)

Assembly Line Balancing	Resource Scheduling
Work element	Activity
Work element's time	Activity resource level
Work station	Project day
Maximum allowable work in any work station (cycle time)	Maximum level of resource per day

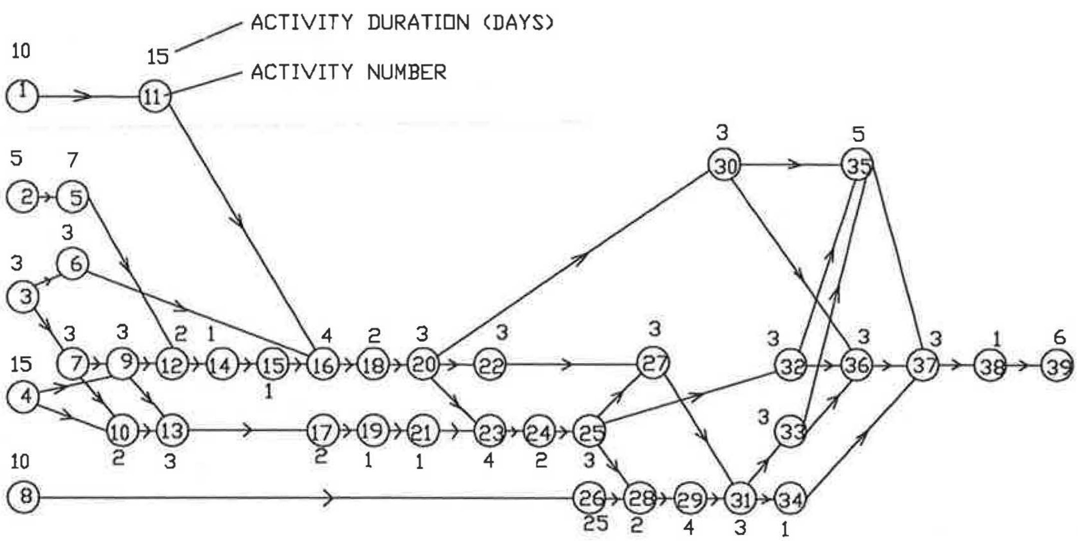

FIGURE 1 Precedence network for bridge construction [based on Clough (4)].

of Activities 33 to 39. This is equal to 25 (3 + 3 + 1 + 5 + 3 + 3 + 1 + 6).

To apply the positional weight method (PWM), a precedence diagram, which should be similar to Figure 1, must be available. The positional weights are then ranked in descending order with the heaviest on the top. The following rules are applied:

1. The activity with the highest positional weight is selected and assigned on the first project day.
2. The unassigned resource per day is calculated by subtracting the assigned resource from the maximum available resource.
3. The activity with the next highest positional weight is then selected, and two checks are to be carried out: (*a*) An activity can only be assigned if all the preceding activities have been assigned (the preceding activities must be complete before the succeeding ones are assigned, and once an activity is started, it cannot be interrupted). (*b*) The resource requirement must be less than or equal to the unassigned resource available for the activity. If both (*a*) or (*b*) are met, then the activity is assigned to the day in question and Steps 2 and 3 are repeated for the activity with the next highest positional weight. If either of the conditions is not satisfied, that activity is bypassed and the activity with the next highest positional weight is selected and the two checks (*a*) and (*b*) are to be carried out.
4. Rules 2 and 3 are repeated for the same project day until at least one of the following conditions prevails: (*a*) the sum of the assigned resources equals the maximum resource level provided, (*b*) no more activities can be assigned because of precedence logic, or (*c*) all the remaining activities have resource requirements greater than the unassigned resources available.
5. The second project day is now considered. Any previously assigned activity cannot be interrupted, hence the resource for that activity is still needed. The activity with the next highest positional weight is then selected.
6. Rules 2, 3, 4, and 5 are then repeated until all activities have been assigned.

BRIDGE CONSTRUCTION PROJECT—EXAMPLE

To illustrate the principles described, it is desirable to consider an example project. The project described is contained in Clough (*4*).

A single-span vehicular bridge is to be erected over a small ravine. It is of composite steel-concrete construction and is of the deck-girder type. The bridge is supported by two reinforced concrete abutments. Each abutment consists of a breast wall and two wing walls and rests on twenty-eight 40-ft-long creosoted timber piles. The reinforced concrete paving slab is 10 in. thick and is supported by seven W 36 × 150 steel floor girders. Concrete curb and aluminum guardrail are provided on each side. Exposed structural concrete is to receive a rubbed finish, and bridge surfaces are to be painted.

Figure 1 shows the network diagram. The activity descriptions are given in Table 2. The contents of work include mobilization, production of shop drawings, material delivery, excavation for abutments, driving piles, casting of footings, backfilling, installation of steel girders, casting of concrete deck, provision of guardrails, painting, cleanup, and final inspection. The project starts in June and ends in September, requiring a total of 70 days. One pile crew, five carpenters, seven ironworkers, four cement masons, two operating engineers, two truck drivers, and seven laborers are the maximum level of resource provided on any single day.

Most of the work is repetitive in nature. A large number of piles are to be driven, two abutments are to be constructed, seven steel floor girders are to be installed, and curb and guardrail are to be provided.

RESOURCE ALLOCATION USING PWM

Resource allocation for the bridge project is carried out using PWM. Resource allocation is carried out one by one. A resource level is first assumed. For example, it may be assumed that a maximum level of six laborers is to be provided. This number should be equal to or greater than the maximum resource requirement. For example, the maximum resource

TABLE 2 Description of Activities (*4*)

Act[1]	Dur[1]	Res[1]	Description
1	10		Produce shop drawings for abutment and deck reinforcement
2	5		Produce shop drawings for footing reinforcement
3	3		Moving in work area
4	15		Deliver foundation piles
5	7		Deliver footing reinforcement
6	3	4C,2L,1OE	Make formwork for abutments
7	3	2L,1OE	Excavate for abutment no. 1
8	10		Produce shop drawings for steel girders
9	3	1OE	Drive piles for abutment no. 1
10	2	2L,1OE	Excavate for abutment no. 2
11	15		Deliver abutment and deck reinforcement
12	2	2C,2L	Placing reinforcement and setting up forms for footing no. 1
13	3	1OE	Drive piles for abutment no. 2
14	1	3L	Pour concrete for footing no. 1
15	1	1C,2L	Strip formwork for footing no. 1
16	4	5C,4L,1OE	Placing reinforcement and setting up forms for abutment no. 1
17	2	2C,2L	Placing reinforcement and setting up forms for abutment no. 2
18	2	1C,6L,1OE	Pour concrete for abutment no. 1
19	1	3L	Pour concrete for footing no. 2
20	3	2C,4L	Strip formwork and cure abutment no. 1
21	1	1C,2L	Strip formwork for footing no. 2
22	3	3L,1OE	Backfilling abutment no. 1
23	4	5C,4L,1OE	Placing reinforcement and setting up forms for abutment no. 2
24	2	1C,6L,1OE	Pour concrete for abutment no. 2
25	3	2C,4L	Strip formwork and cure abutment no. 2
26	25		Deliver steel girders to site
27	3	3L,1OE	Backfilling abutment no. 2
28	2	1L,1OE	Placing steel girders
29	4	5C,4L,1OE	Placing steel and formwork for deck
30	3		Rub concrete surface for abutment no. 1
31	3	1C,6L,1OE	Pour concrete and cure for deck
32	3		Rub concrete surface for abutment no. 1
33	3	5C,6L,1OE	Stripping deck formwork
34	1	1L	Saw cut joints on deck
35	5	4L	Painting work
36	3		Install guard rails
37	3		Cleaning up
38	1		Final site inspection
39	6		Contingency for delays

[1]Note:- Act: Activity; Dur: Duration (days); Res: Resource provided (no.); C: Carpenter; L: Laborer; OE: Operating Engineer.

requirement for laborers is six, and this is the minimum level to be provided. Once a resource level is decided, the procedure described for PWM can be applied. It is assumed that other resources are adequately provided so that the project is not delayed because of a shortage of other resources. A project duration and the daily resource requirement can be obtained using the PWM. This method is repeated for a higher level of resource so that a minimum project duration is achieved. After allocation of this resource is finished, allocation of other resources is carried out.

Step 1

Positional weight ranking is required. This is provided in Table 3. To apply Rule 1, Activity 4 is selected because the positional weight for that activity is the highest. The activity is assigned on the first day.

TABLE 3 Positional Weight Ranking

Activity Number	Positional Weight (Days)
4	92
3	86
1	86
7	80
2	77
11	76
9	75
5	72
8	66
12	65
6	64
14	63
15	62
16	61
18	57
26	56
20	55
10	55
13	53
17	50
19	48
21	47
23	46
24	42
25	40
28	31
22	31
29	29
27	28
31	25
33	21
32	21
30	21
35	15
36	13
34	11
37	10
38	7
39	6

Step 2

Following Rule 2, the unassigned resource per day is calculated. Because the maximum level of resource provided for the laborers is seven and the laborer requirement for Activity 4 is zero, the unassigned resource per day is 7 (7 − 0).

Step 3

In accordance with Rule 3, Activities 1 and 3 are both selected because they have the next highest positional weight (86 days). Before either is assigned, it is necessary to carry out the two checks.

Because there is no preceding activity for Activities 1 and 3, Rule 3a is met. The laborer requirement for both is zero. This is less than the unassigned resource (7 > 0). Conditions 3a and 3b are met, and Activities 1 and 3 are both assigned on the first day.

Steps 2 and 3 are then repeated for the activity with the next highest positional weight.

Activity 7 has the next highest positional weight (80 days). According to Condition 3a, preceding activity has to be completed before assignment can be considered. The preceding activity for Activity 7 is Activity 3. This activity has a duration of 3 days. Thus Condition 3a is not met, and Activity 7 cannot be assigned.

Activity 2 is now considered because it has the next highest positional weight (77 days). It can be seen that Conditions 3a and 3b are met by this activity, and this activity is also assigned on the first project day.

Activity 11 has the next highest positional weight (76 days), and this is considered. The preceding activity is Activity 1. Because the activity duration is 10 days, this activity is not yet finished and according to Condition 3a cannot be assigned. Similarly, Activities 9 and 5 cannot be assigned.

Activity 8, which has the next highest positional weight (66 days), is now considered. Conditions 3a and 3b are met, so this activity is assigned. Up until now, Activities 4, 3, 1, 2, and 8 have been assigned. Because of Condition 3a, no more activity can be assigned until after 3 days, the duration of Activity 3.

Step 4

The fourth day is now considered. Activity 7 is considered because it has the highest positional weight (80 days). Condition 3a is met, and because Activity 7 requires two laborers, which is less than seven, this activity is assigned. Similar reasoning applies for Activity 6, and there is a surplus of three laborers.

Step 5

The earliest date an activity can be assigned is Day 6, because Activity 2 finishes on Day 5. Activity 5 is assigned because conditions 3a and 3b are met. No other activities can be assigned on this day because of precedence logic. The foregoing procedure is repeated for other activities. The order in which the activities are assigned is given in Table 4.

RESULTS

Using AssemBalance, which is a computer program based on PWM for resource allocation, resource requirements and project duration are obtained. This solution is also possible by hand calculation, which is neither complicated nor difficult to apply.

The minimum project duration is 70 days. The minimum levels of resource required are five carpenters, seven laborers, and two operating engineers. This is better than the solution reported by Clough (*4*), which required six carpenters instead of five, seven laborers, and two operating engineers, for the same project duration. The solution was obtained using CPM. Because the minimum requirement for various activities is five, the level cannot be reduced any further. PWM is superior and easier to use, and resource usage is minimized.

TABLE 4 Order of Activity Assignment

Order of Assignment	Activity Number
1	4
2	3
3	1
4	2
5	8
6	7
7	6
8	5
9	11
10	26
11	9
12	10
13	12
14	13
15	14
16	15
17	17
18	19
19	21
20	16
21	18
22	20
23	23
24	22
25	30
26	24
25	25
26	28
27	27
28	32
29	29
30	31
31	33
34	34
35	35
36	36
37	37
38	38
39	39

The duration of a project is affected by the level of resource provided. In the case of laborers, reducing the number by one increases the project duration by 4 days. It is not possible to reduce the number of carpenters any further, as explained. Reducing the number of operating engineers by one increases the duration of the project by 3 days.

Increasing the work force from 5, 7, and 2 for carpenters, laborers, and operating engineers, respectively, to a higher level, even up to 20 for each trade, does not reduce the project duration any further. The minimum project duration is still 70 days. This is the critical path duration.

A bar chart showing the resource requirement and start day and finish dates for the resources is shown in Figure 2.

ASSEMBALANCE

AssemBalance is written in GW-BASIC Version 3.20, which is one of the most popular engineering computer languages. BASIC is perhaps the cheapest computer language package obtainable and is readily available to personal computer users. There is no need to purchase other software (other than a BASIC package) to run AssemBalance. This fact should enable AssemBalance to be more widely applicable.

Other project management programs based on CPM are available. In general, they are more difficult to use, partly because of the complexity of the CPM technique itself.

AssemBalance is user interactive. The software allows easy inputting. In case mistakes are entered, the program provides opportunities for corrections.

DISCUSSION OF RESULTS

PWM is extremely easy to apply, and it provides solutions not only to a URS problem but also to a CRS problem. There is no need to first determine a critical path. These are excellent advantages.

A better solution is possible with this method than with CPM. Instead of six carpenters, only five are needed without delaying the project, thus saving project expenses.

Compared with linear programming, this method requires little computational effort. There is no need to set up an objective function and resource constraint equations. Hence, another computational difficulty is avoided. Furthermore, PWM produces a critical path as a by-product.

The solution obtained is relatively robust in the sense that even if a mistake is made, a good solution is still possible. For example, if the positional weight for Activity 37 is miscalculated, the final solution is still the same. This is because PWM depends not only on the positional weight but also on the precedence logic.

CONCLUSION

The example indicates that assembly line balancing can be of great value to the scheduling of highway and other projects. The method is simple, and there is no need to get into the complexity of obtaining the critical path.

```
                            1                   2                   3
Day       1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4
-------------------------------------------------------------------------------------
Activity                                                                            Activity
26                            * * * * * * * * * * * * * * * * * * * * * * * *       26
25                                                                                  25
24                                                                                  24
23                                                                                  23
22                                                                                  22
21                                                        * 2L,1C                   21
20                                                              4L,2C * * *         20
19                                                      * 3L                        19
18                                                                    * * 6L,1C,1OE 18
17                                                    * * 2L,2C                     17
16                                                            * * * * 4L,1OE,5C     16
15                                                    * 2L,1C                       15
14                                                      * 3L                        14
13                                              * * * 1OE                           13
12                                              * * 2L,2C                           12
11                            * * * * * * * * * * * * * * *                         11
10                                        * * 2L,1OE                                10
9                                         * * * 1OE                                 9
8         * * * * * * * * * *                                                       8
7               * * * 2L,1OE                                                        7
6               * * * 2L,4C                                                         6
5                   * * * * * * *                                                   5
4         * * * * * * * * * * * * * * *                                             4
3         * * *                                                                     3
2         * * * * *                                                                 2
1         * * * * * * * * * *                                                       1
-------------------------------------------------------------------------------------
```

LEGEND: * * * 2L,1OE,4C - 2 LABORERS, 1 OPERATING ENGINEERS AND 4 CARPENTERS ARE REQUIRED FOR THREE DAYS (ONE ASTERISK REPRESENTS ONE DAY)

(a)

```
          Day
          3         4                   5                   6                   7
          5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0
-------------------------------------------------------------------------------------
Activity                                                                            Activity
39                                                                * * * * * *       39
38                                                              *                   38
37                                                        * * * 4L                  37
36                                              * * * 1L                            36
35                                              * * * * *                           35
34                                        *                                         34
33                                        * * * 6L,1OE,5C                           33
32                          * * *                                                   32
31                                  * * * 6L,1OE,1C                                 31
30        * * *                                                                     30
29                            * * * * 4L,1OE,5C                                     29
28                          * * 1L,1OE                                              28
27                          * * * 3L,1OE                                            27
26        *                                                                         26
25                    * * * 4L,2C                                                   25
24                * * 6L,1OE,1C                                                     24
23        * * * * 4L,1OE,5C                                                         23
22        * * * 3L,1OE                                                              22
-------------------------------------------------------------------------------------
```

LEGEND: * * * 2L,1OE,4C - 2 LABORERS, 1 OPERATING ENGINEERS AND 4 CARPENTERS ARE REQUIRED FOR THREE DAYS (ONE ASTERISK REPRESENTS ONE DAY).

NOTE: WHERE RESOURCES ARE NOT INDICATED, IT IS EITHER
(1) NO RESOURCES ARE REQUIRED (FOR EXAMPLE, CONTINGENCY FOR DELAY) OR
(2) ANALYSIS HAS NOT BEEN PERFORMED ON THAT PARTICULAR ACTIVITY (ONLY THREE TYPES OF RESOURCES ARE CONSIDERED FOR THE PURPOSE OF ILLUSTRATION).
IN THE CASE OF (2), UNCONSTRAINED RESOURCE IS ASSUMED.

(b)

FIGURE 2 Bar chart showing resource requirement and activity start and finish dates: *a*, Days 1 to 34; *b*, Days 35 to 70.

Much computational time can be saved and human errors can be reduced because the method is much simpler to apply. Because there is no special machine requirement, PWM can be successfully applied on site. The content of the work is likely to be changed because of design variations and unforeseen ground conditions, so modification of the precedence network is also necessary. Using PWM, the project duration and resource requirement can again be obtained readily.

An unexpected outcome of this method is that a critical path can be obtained as a by-product. Thus, this method is of importance not only to resource scheduling but also to project planning.

PWM can be used to solve both constrained and unconstrained resource allocating problems. The capability is of great use to resource planning because both problems are likely to occur in construction.

AssemBalance is easy to use and is user interactive. Little input information is required to run the program. The program is written on GW-BASIC, so the software required to run the program is minimal. There is also little machine dependence, because the program can be run on an IBM PC.

ACKNOWLEDGMENT

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Analyzing Linear Construction Operations Using Simulation and Line of Balance

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The results of an investigation involving the use of simulation and the line of balance concept to analyze linear construction operations are presented. The line of balance concept is presented, its benefits and limitations are discussed, and the barriers to its implementation are addressed. The statistics collection capabilities of MicroCYCLONE, a Monte Carlo discrete event process interaction simulation program that lends itself to the modeling of construction process applications, were enhanced to foster the monitoring of partially completed production units and stage buffer quantities for repetitive processes during the simulation of a linear construction operation. The enhancements provide the information necessary to perform line of balance analyses of linear construction models. Statistics collected with the enhancements can be used to generate realistic production flow line curves and stage buffer charts at multiple locations in a single model as time evolves. These graphical plots can be easily used to identify potential bottlenecks, to determine what is wrong with an operation, and to design corrective measures for improving system performance. The significance, capabilities, and implementation of the statistics collection enhancements are discussed. An illustrative case study is provided.

Linear construction operations are operations that involve repetitive units of construction elements. Some classic examples of linear construction projects include highways, high-rise buildings, tunnels, and pipelines. The repetitive construction units of these four examples can be expressed in terms of number of road sections, floors, tunnel rings, and lengths of pipe, respectively. Each of these repetitive units can be further subdivided into a sequence of processes that is repeated for each unit of the operation. For example, the sequence of processes for a road construction operation may include earth hauling, base delivery, base spreading, and asphalt rolling. Linear construction operations often consist of repetitive processes with different production rates. This phenomenon of production rate imbalance, which is shown in Figure 1, has the potential for negatively affecting project performance by causing work stoppages, inefficient use of allocated resources, and excessive costs. Production rate imbalance occurs when the production curves of "leading" processes intersect the line of balance (LOB) curves of "following" processes because of different production rates (i.e., production curve slopes) and insufficient lag between start times of processes.

The results of an investigation involving the simulation analysis of linear construction operations using the LOB concept are presented.

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LOB CONCEPT

The LOB method consists of a family of graphical or analytical linear scheduling techniques including the time space scheduling method (TSSM) (*1*), vertical production method (VPM) (*2*), velocity diagrams (*3*), linear scheduling method (LSM) (*4,5*), repetitive project model (RPM) (*6*), and LOB scheduling (*7–9*).

The LOB method was originated by the Goodyear Company in the early 1940s and was developed by the U.S. Navy during World War II for the programming and control of both repetitive and nonrepetitive projects (*10*). Because of the immense popularity of network scheduling techniques including the critical path method (CPM) in this country, the LOB technique has never been fully developed and implemented by the U.S. construction industry. However, there has been a higher level of use of this method by European contractors (*11*). The method has been applied to repetitive construction projects (*12*), planning of residential construction (*13*), resource scheduling and coordination among subcontractors (*14*), the scheduling of road pavement projects (*12*), and modeling production activities for multifacility projects (*15*).

Typical process production (or flow line) curves are shown in Figure 2. The production curves for Processes B and C are plotted in terms of stage number as a function of time. Stages represent the cumulative number of production units completed at a certain time (e.g., number of floors, number of road sections, etc.). The production rate for a process can be determined from its slope and expressed in terms of units per time. The horizontal distance between the production curves for two consecutive processes at a particular stage represents the lag or time buffer between those processes at that stage. The vertical distance between production curves for two consecutive processes at any given time represents the stage buffer (i.e., number of units in queue between processes) at that time.

From a set of process production curves for a linear operation as shown in Figure 1, an aggregate production curve for the overall operation can be determined using a variety of graphical or analytical techniques. The overall production curve is referred to as the LOB for the operation. The LOB concept can be applied to the manufacture or construction of any linear operation, such as sections of road completed, the number of washing machines produced, and so forth (*13*). LOB methodology can be used to determine at any given time (*a*) shortages of delivered materials that may affect production; (*b*) materials that are being delivered in excess, which may cause additional material handling or require additional storage space; (*c*) the jobs or processes that are falling behind

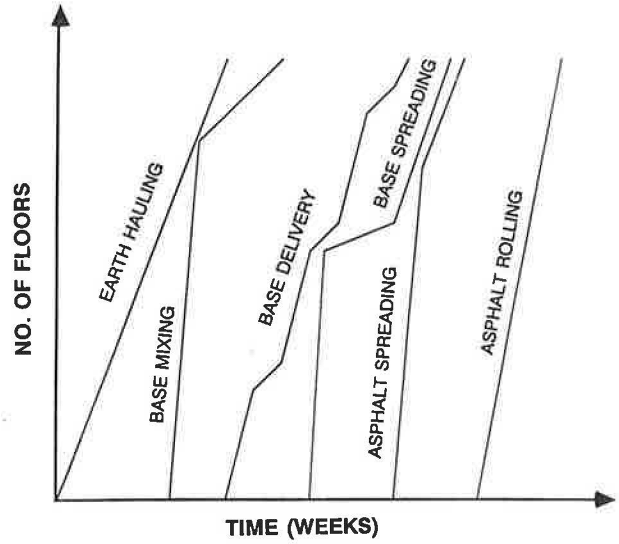


FIGURE 1 Production (or flow line) curves for repetitive processes.

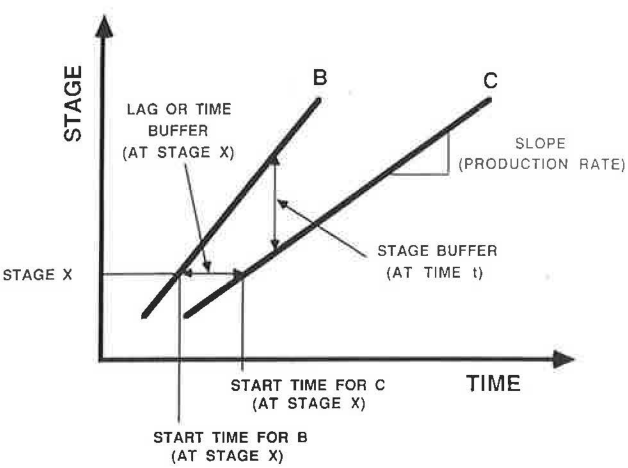


FIGURE 2 Process production curves (*6*).

and the required rate of production to satisfy the required LOB quantities; (*d*) the jobs or processes that are ahead of schedule, which may be placing heavier demands on operating capital than necessary; and (*e*) a forecast of partially completed production units by job, workstation, or process to support the delivery schedule of finished units (*13*).

Benefits and Limitations

As stated earlier, the major benefit of the LOB methodology is that it provides production rate and duration information in the form of an easily interpreted graphics format. The format involves the generation of production curves for the repetitive processes, as shown in Figure 1. The LOB plot for a linear construction operation can easily be constructed, show at a glance what is wrong with the progress of a operation, and detect potential bottlenecks.

Although LOB methodology can be used to aid in the planning and control of any type of operation, it is better suited for application to linear than to nonlinear operations. A major limitation of the LOB methodology is that it assumes that production rates are linear (i.e., constant rate of production over time). Because of the stochastic nature of construction processes (*7*), the assumption that production rates of construction projects and processes are linear may be erroneous. Another limitation of the LOB methodology is that it does not lend itself well to computer computations. In addition, the objective of many planning techniques based on the LOB concept is to reduce project duration with little or no regard for project cost (*6*).

Barriers to Implementation

Despite the broad use of LOB by the European construction industry (*11*), the U.S. Navy (*10*), and the manufacturing industry, the application of LOB by the U.S. construction industry has been very limited. Some barriers to implementation of the LOB methodology include the following:

1. There is a lack of awareness among practitioners in the U.S. construction industry that the LOB methodology exists (*10*).
2. Owners and contractors began adopting network techniques as planning tools at about the same time that the LOB methodology was originated and developed. These entities are reluctant to adopt new planning tools that are not being used by their counterparts or competitors (*13*).
3. Network techniques can be easily computerized, whereas the LOB methodology does not lend itself well to computerization. Because of the popularity of the relatively inexpensive microcomputer in the U.S. construction industry, there is a resistance to changing to a planning method that is not currently supported by computer.

OPERATION MODELING

Construction Simulation Systems

In the construction domain, the use of simulation has involved either a commercial simulation package (e.g., GPSS, SIMAN, SIMSCRIPT, SIMULA, SLAM, etc.) or a custom-developed simulation package designed to model the unique characteristics of construction projects. Simulation packages developed specifically for application to construction operations include MicroCYCLONE, INSIGHT, RESQUE, and STEPS. These packages are all based on the CYCLONE (CYCLic Operation NEtwork system) modeling format developed by Halpin (*16*). The MicroCYCLONE modeling elements are shown in Figure 3.

MicroCYCLONE is a microcomputer-based version of CYCLONE developed by Halpin (*16,17*). INSIGHT (INteractive SImulation of construction operations using GrapHical Techniques) was developed by Kalk (*18*) as a separate implementation of the CYCLONE modeling system. Working with Carr, Chang (*19*) developed RESQUE (REsource based QUEueing network simulation) based on the CYCLONE

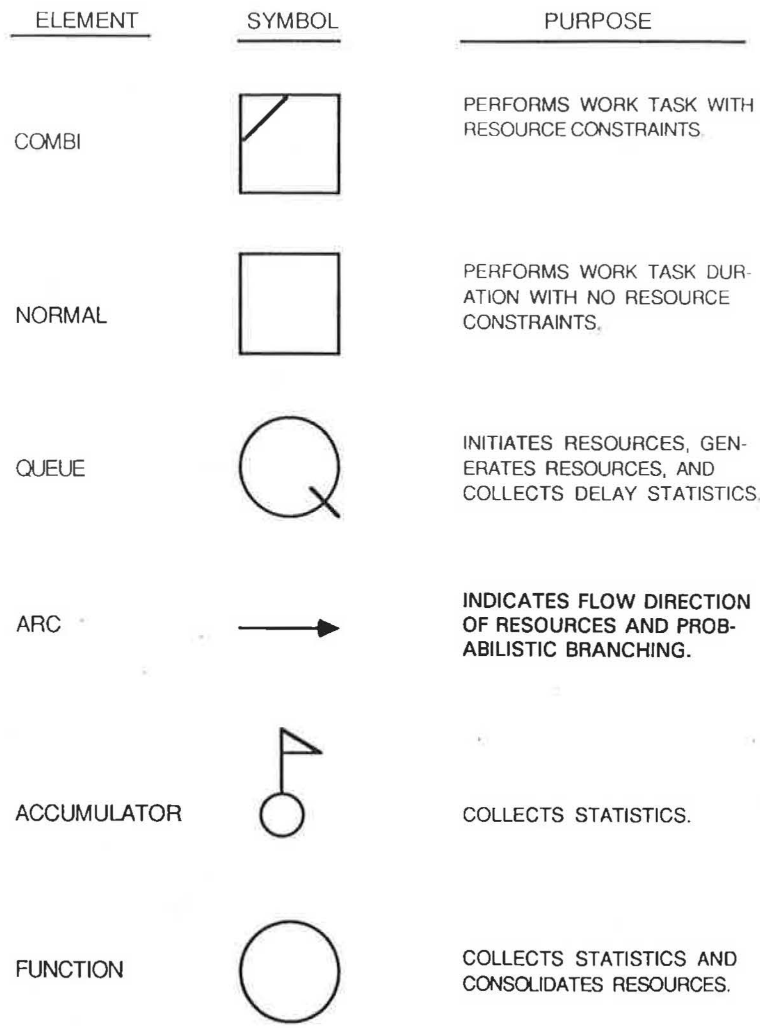


FIGURE 3 MicroCYCLONE modeling elements (*7*).

modeling format, which allows the modeling of nonidentical resources. A new construction simulation package for planning horizontal earthwork operations called STEPS (STructured Environment for Process Simulations) was recently developed as part of a joint research project between the University of Maryland and the U.S. Naval Civil Engineering Laboratory (*20*).

MicroCYCLONE is a Monte Carlo system that uses discrete event process interaction simulation to model and simulate the interaction between resources as resource units flow through a model. CYCLONE was developed to overcome the limitations of existing methods, including CPM, PERT, queueing theory, and GERT (*21*). Time and production parameters are calculated and stored in data files as resource units cycle in the model until the end of the simulation period has been realized.

Breakdown of Construction Operations

The sequential logic of necessary processes for an operation can be conceptually modeled using a link-node diagram. A link-node diagram of a simple road construction operation including earth hauling, base delivery, base spreading, and asphalt rolling is shown in Figure 4.

A link-node diagram consists of links representing the cycling of equipment units between two locations and nodes representing points of transfer between two links. In a study performed by Teicholz (*22*), a two-link diagram was used to depict simulation models for simple construction systems involving a server (loader, pusher, etc.) and a processed unit (truck, tractor scraper, etc.). An example of a three-link diagram is a paving material distribution system (*23*) in which the first link represents the generation of asphalt batches, the second link represents the cycling of the trucks between the batch plant and the pavers, and the third link represents the cycling of the pavers. The road construction operation discussed here is a four-link simulation system.

The link-node diagram can be extended to model a linear construction project in a LOB context where links and nodes denote individual repetitive processes and stage buffers, respectively. For the purpose of this investigation, a process was defined as a group of related work tasks that transform or transport resources to produce partially completed work

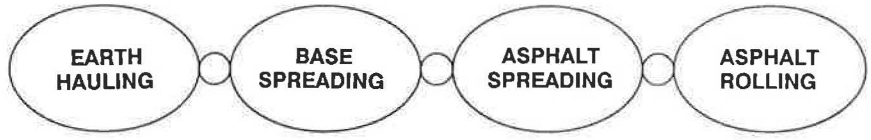


FIGURE 4 Link-node diagram of the road construction model.

units. Once a process yields a partially completed work unit (i.e., section for the road construction example) it enters a stage buffer or storage queue to await entry into the next process. If the next process is ready for the partially completed work unit, it moves directly into the next process with no waiting in the stage buffer. If the next process is busy, partially completed work units may build up in the stage buffer. When a stage buffer is empty and the next process is idle, a work stoppage can occur.

By collecting intermediate statistics for partially completed work units as they move through stage buffers from one repetitive process to the next, process cycle monitoring and stage buffer monitoring can be fostered during a simulation. Process cycle monitoring can be used to generate theoretical process production curves, system constrained production curves, and the LOB. Stage buffer monitoring can be used to generate stage buffer charts depicting the number in queue as time evolves during the simulation.

STATISTICS COLLECTION

The existing MicroCYCLONE Version 2.5 provides a report for process cycle monitoring reflecting the task repetition number and corresponding simulation time for COMBI (i.e., a work task constrained by resources) and NORMAL (i.e., a work task not constrained by resources) elements. The term "process cycle monitoring" as used in this paper denotes the collection and recording of process repetitions (i.e., completion of production units or production cycles) and corresponding simulation times for distinct processes during the simulation of a multiple-process operation.

The stage buffer monitoring enhancement presented here allows the user to track quantities of partially completed production units at any point in a model during a simulation. Stage buffers are work reservoirs that occur at queues between individual processes (*13*). When a stage buffer becomes empty, the following process must remain idle until a production unit enters the preceding stage buffer. When a stage buffer has one or more units, the following process continues to operate without interruption.

Enhancement Methodology

Although intermediate statistics required to measure process production rates and stage buffer quantities are calculated by the existing MicroCYCLONE program, only final statistics are retained for the user. Under the direction of Halpin, Lutz (*24*) developed process cycle and stage buffer monitoring enhancements for use with MicroCYCLONE. The enhancements consisted of the coding of several subroutines to foster the collection and recording of initial, intermediate, and final process and stage buffer statistics.

The simulation flow diagram for MicroCYCLONE is shown in Figure 5. As shown in Figure 5, the code enhancement facilitates the collection of intermediate statistics after the termination of work tasks associated with end event time (EET) and before units are released from the terminated elements. The enhancement works in conjunction with existing CYCLONE methodology and modeling elements to perform process and stage buffer monitoring.

Process cycle monitoring statistics required for analyzing linear construction operations include the process production cycle number as time evolves during the simulation for certain FUNCTION elements (e.g., non-COUnter and non-CONsolidate FUNCTION elements) for multiple-process models. The current version of MicroCYCLONE allows the use of one ACCUMULATOR and multiple FUNCTION elements for a single model. These elements provide for the collection of production cycle statistics and final statistics, respectively. The existing SIMULA module of MicroCYCLONE generates these intermediate statistics but does not capture them in report form for the user. The process cycle monitoring enhancement consists of several small subroutines in SIMULA that essentially allow the user to place counters at multiple locations in the same model.

Stage buffer monitoring statistics required for analyzing linear construction operations included the number in queue as time evolves during the simulation for stage buffer QUEUE elements placed between individual processes in a multiple-process model. As in the case of the process cycle monitoring enhancement, the existing SIMULA module of MicroCYCLONE generated these intermediate statistics but did not capture them in report form for the user. The stage buffer monitoring enhancement consists of several small subroutines in SIMULA that allow the user to place SINK elements between processes of multiple-process models.

Statistics Collection Mechanism

As shown in Figure 6, the statistics collection mechanism consists of a FUNCTION element followed by a SINK element. The developed statistics collection mechanism provides two new features to the existing MicroCYCLONE program; it allows the use of multiple counters in a single model and tracks the number of partially completed production units in queue as time evolves during the simulation for SINK elements. The existing program only allowed the use of one counter in a single model. The SINK element performs the same function as a QUEUE element and has typically been used at the end of the model to collect completed production units. However, multiple SINK elements can now be used in

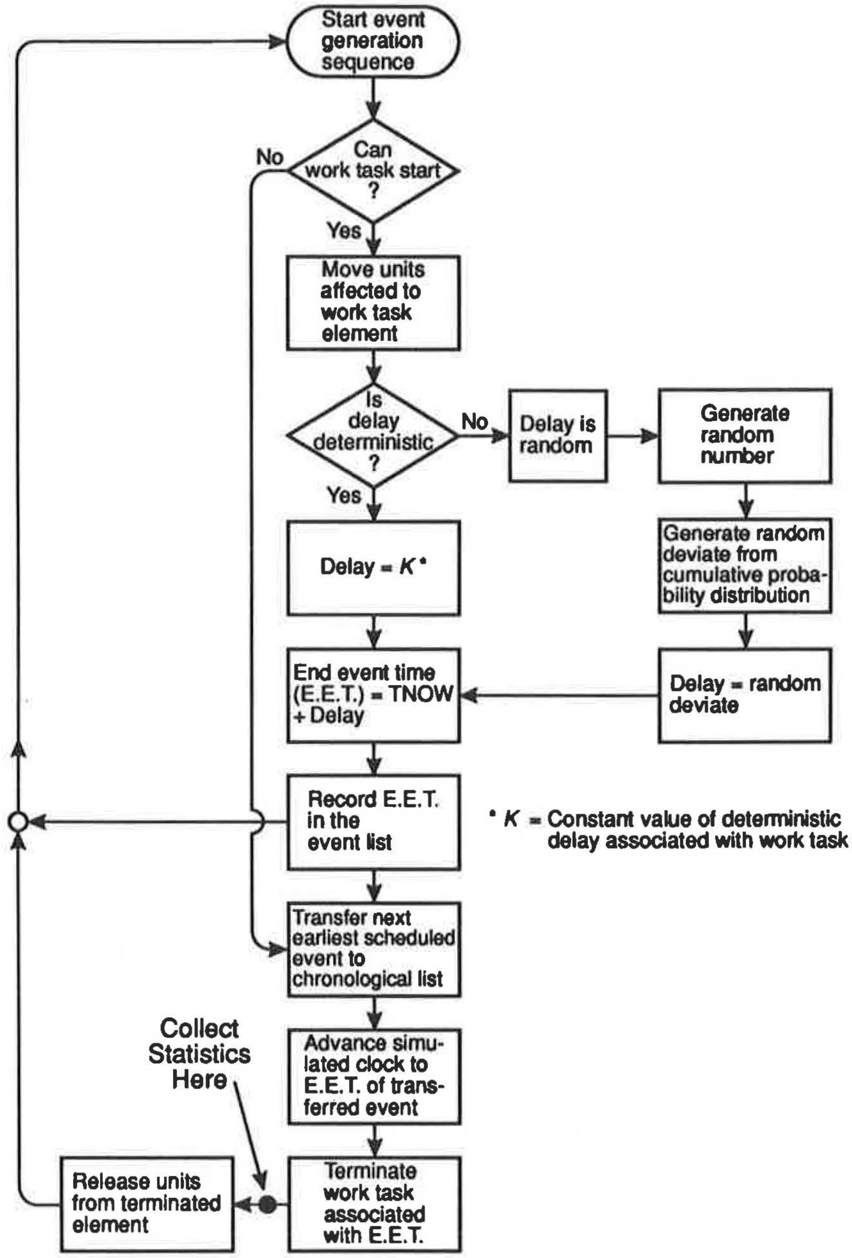


FIGURE 5 MicroCYCLONE simulation flow diagram (*7*).

the place of QUEUE elements in a single model to collect additional statistics.

Collection of Statistics

One application of the statistics collection mechanism is to foster the collection of statistics for individual processes during the simulation of a multiple-process linear construction model as shown in Figure 6. This can be accomplished by inserting a statistics collection mechanism after each distinct process in the model. Additional statistics (i.e., element label, cycle number, and simulation time) are collected in a file on the specified data disk entitled "*filename*.FUN" for non-CON and non-COU FUNCTION elements. Additional statistics (i.e., element label, quantity in buffer, and simulation time) are collected in a file on the specified data disk entitled "*filename*.QUE" for SINK elements. These elements are specified in the Network Input statements as discussed in the MicroCYCLONE User's Manual (*17*).

After a simulation has been completed, the statistics collection files (i.e., "*filename*.FUN" and "*filename*.QUE") are imported into a spreadsheet program for data manipulation as required. As shown in Figure 6, these data are used to generate system constrained process production or flow line curves (i.e., curves representing the realistic production be-

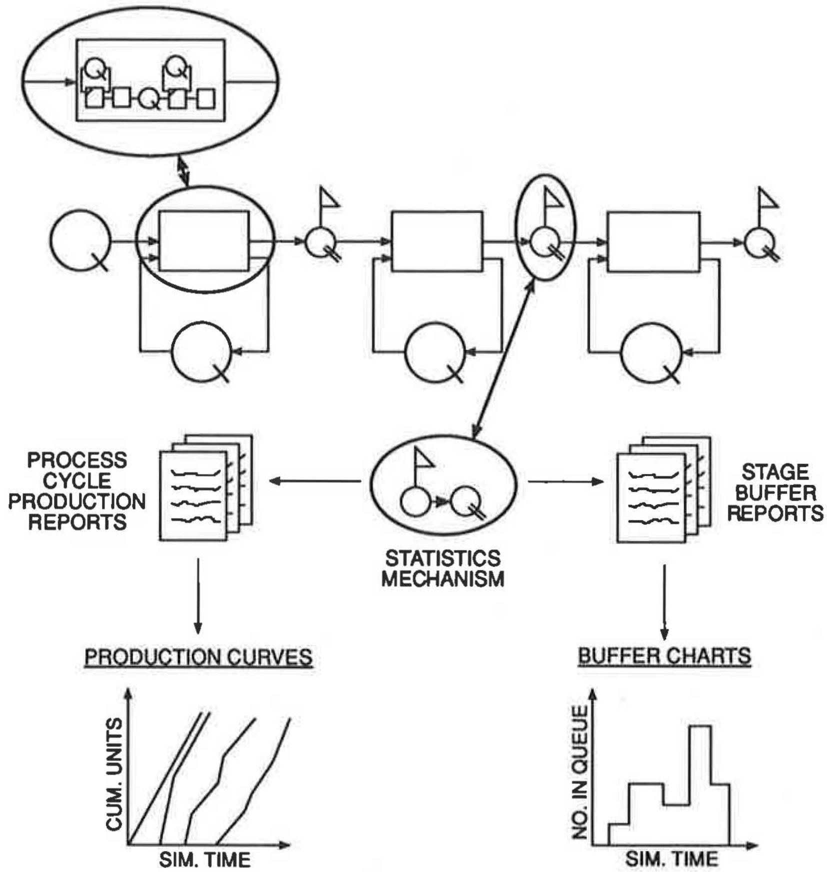


FIGURE 6 Process cycle and stage buffer monitoring enhancements.

havior of individual processes in a multiple-process model as constrained by the system during simulation) and to generate stage buffer charts. A statistics collection mechanism consisting of a generic FUNCTION element followed by a SINK element was developed to collect initial, intermediate, and final statistics between processes. The statistics collection enhancements of MicroCYCLONE are significant because they allow the user to collect statistics anywhere in a simulation model instead of at just one location, as previously provided by the program. By placing statistics mechanisms between processes of a multiple-process model, process production flow line curves and stage buffer charts can be generated. These graphical plots can be easily used to identify potential bottlenecks, to determine what is wrong with an operation, and to design corrective measures to improve system performance.

SIMULATION ANALYSIS

Seven operations were selected for simulation experimentation using the LOB concept: a precast concrete plant, stone cutting plant, match casting plant, steel erection, sewer line installation, road construction, and high-rise building construction. The experimental methodology used and the results from an illustrative case study involving a road construction model are provided.

Experimental Methodology

Each of the seven operation models was broken down into a set of individual processes and stage buffers using the previously described systematic approach. For each operation, stochastic simulations were performed for each individual process and for the overall operation using controlled random number streams. The mean simulation cycle times from these runs were used to plot the theoretical set of flow line curves and the LOB for the operation. The theoretical plot is based on entering work units being abundant (i.e., the ideal production curves disregarding the other processes in the operation), and the LOB plot is based on the simulation of the overall operation. Since interdependencies between processes are ignored for the theoretical curves, the curves all begin at the origin and may intersect.

Models were then developed for the seven operations using the previously discussed statistics collection enhancements. Statistics collection mechanisms were positioned between individual processes to monitor the production rate and buildup of partially completed production units for each process. Stochastic simulations were performed using controlled random number streams. Mean simulation cycle times and buffer quantities were used to produce sets of system-constrained flow line curves, the overall LOB, and buffer charts. System-constrained production curves begin when the processes are actually initiated during the simulation and cannot intersect, since processes are affected by the characteristics and production rates of preceding processes. The buffer charts provide plots of the quantity of partially completed production units in queue between processes during the simulation.

Case Study: Road Construction Operation

The road construction case study involves the installation of the base and asphalt layers onto a prepared subgrade. The project involves eight separate processes. Since some of the processes are rather involved, detail to the subprocess level has been provided. Process models were obtained from Halpin's (*17*) standard model library, and time durations were based on job history data and estimates based on *Caterpillar Performance Handbook* (*25*) and other references. Major resources include a base mixing plant and an asphalt mixing plant. Material stockpiles include stockpiles for earth, base mix materials, and asphalt materials. The processes include earth hauling, base mixing, base delivery, base spreading, asphalt loading, asphalt delivery, asphalt spreading, and asphalt rolling.

The MicroCYCLONE model for the road surface construction is presented in Figure 7 with no shared resources. The resource requirements for each process have been itemized. Equipment breakdown and a constant incremental increase in travel time have been modeled for the three transportation processes. The processes are stochastic.

Theoretical Production Curves

The theoretical production curves and LOB for the road construction operation are shown in Figure 8. Several observations can be made about the project by analyzing the curves. First, the phenomenon of production rate imbalance exists because the production rates or slopes of the eight processes are not consistent. Second, some of the production curves for the individual processes are approximately linear, whereas others are nonlinear. Some of the curves exhibit the effect of constant change in travel time. Third, the constraining process for the road construction case study is the base delivery process since it dictates the slope of the overall production curve. Fourth, a potential exists for the buildup of partially completed units between the earth hauling and base mixing processes and between the base mixing and base delivery processes. Fifth, the production curves for three of the processes—base spreading, asphalt spreading, and asphalt rolling—are clustered together

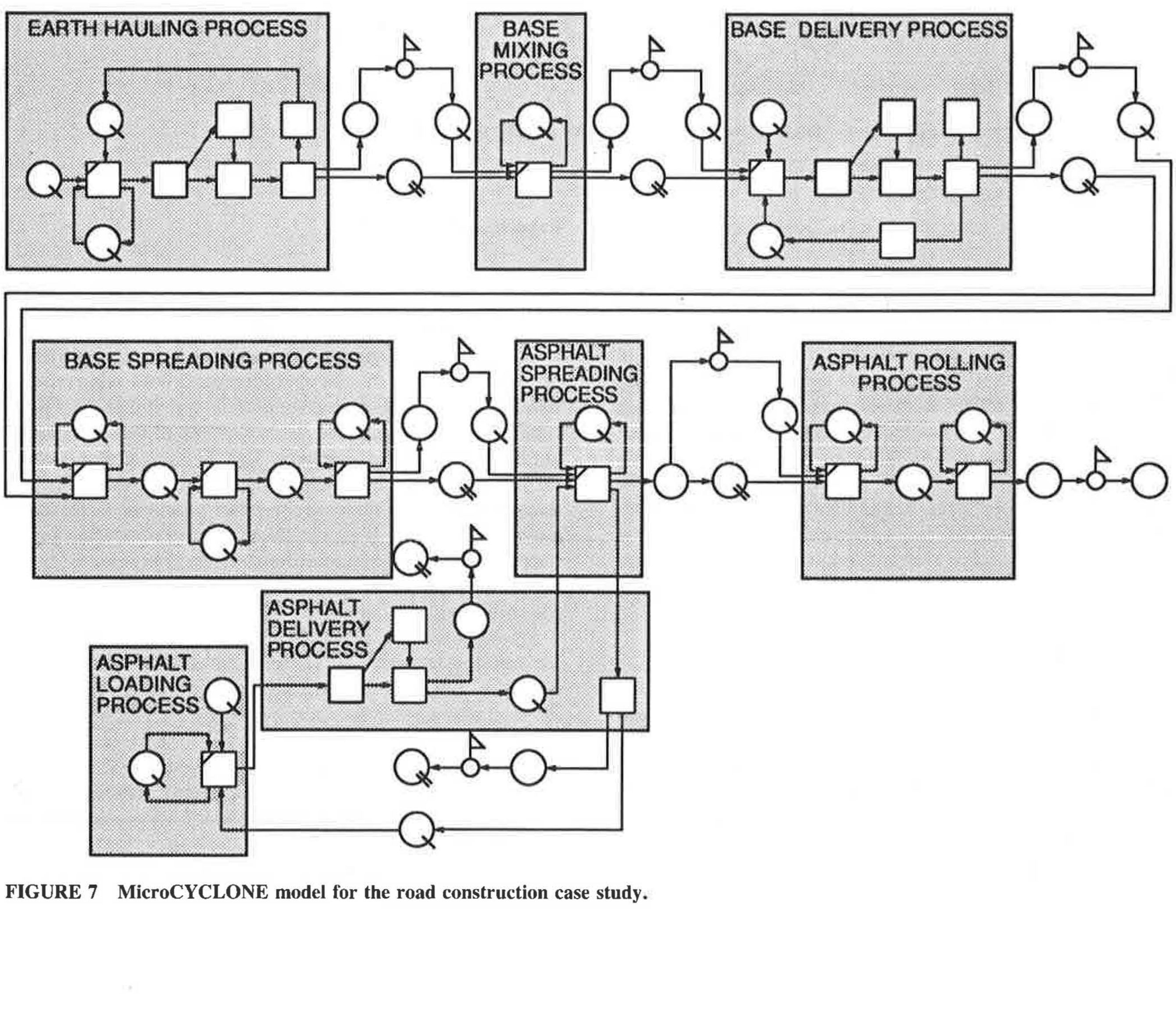


FIGURE 7 MicroCYCLONE model for the road construction case study.

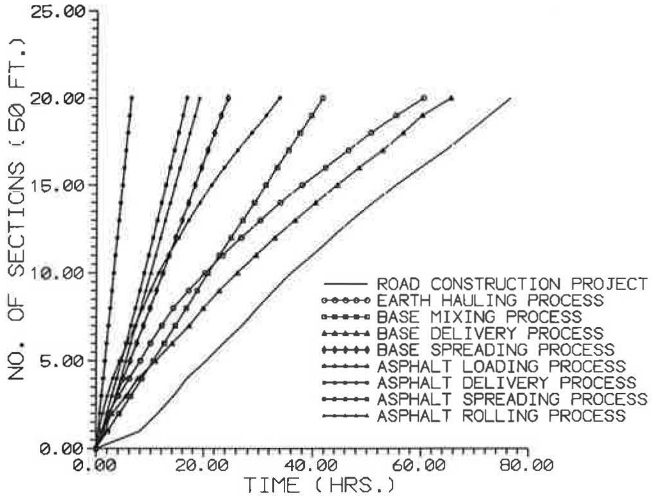


FIGURE 8 Theoretical process production curves for the road construction case study.

with a similar slope; these three processes are approximately balanced.

System-Constrained Production Curves

The system-constrained process production curves yielded from the data provided in the process monitoring report for the road construction processes are presented in Figure 9. Each of the eight production curves is either approximately linear or approximately curvilinear. The curves fall under two general slope categories; the earth hauling and base mixing processes have approximately the same slope, and the six remaining curves have approximately the same slope. The earth hauling process include a transportation cycle with constant increase in travel time. This nonstationarity effect is evident in the shape of the earth hauling and base mixing processes.

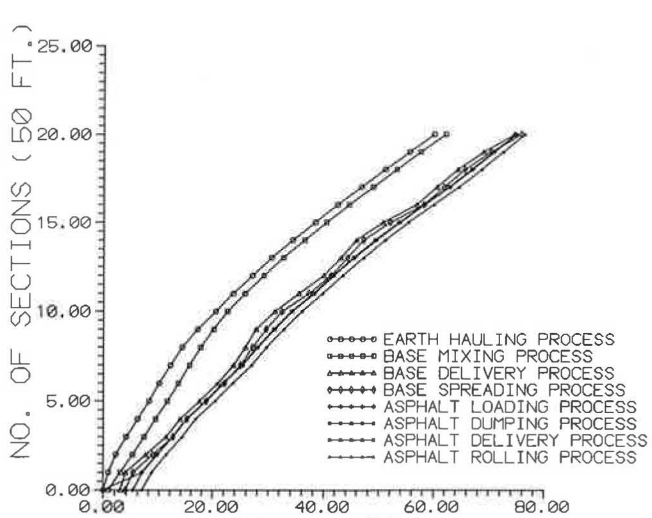


FIGURE 9 System-constrained process production curves for the road construction case study.

An analysis of the production results (*24*) indicated that the constraining process for the group of five processes is the base delivery process (i.e., the base delivery process is the slow runner of the relay team). The earth hauling process does not appear to initially constrain the base mixing process. However, approximately 20 hr into the simulation the diminishing slope of the earth hauling curve because of nonstationarity appears to begin constraining the base mixing curve. As with the theoretical curves, it appears that stage buffers located between the earth hauling and base mixing processes and between the base mixing and base delivery processes may have the potential for buildup of partially completed production units.

It is apparent from the theoretical and system-constrained production curves that the overall production of the road construction project could be improved if the production rates for the earth hauling, base mixing, and base delivery processes were enhanced. A base mixing plant with a larger capacity and additional trucks for the earth hauling and base delivery processes should increase performance of the overall operation.

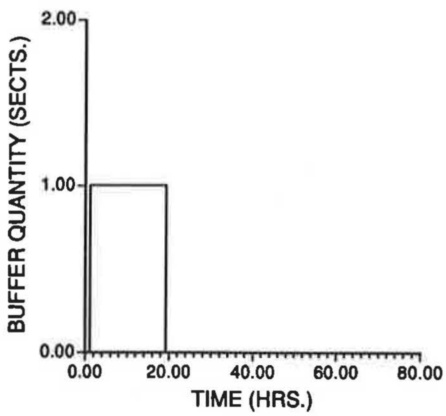
Buffer Charts

On the basis of the data from the stage buffer monitoring report, it was determined that only two stage buffers accumulated partially completed road sections during the simulation. As surmised from the theoretical and system-constrained production curves, the stage buffers immediately following the earth hauling and base mixing processes accumulated partially completed units. The stage buffer charts for the buffers following the earth hauling and the base mixing processes are shown in Figure 10. One road section is built up in the stage buffer (Statistics Collection Mechanism 1) preceding the base mixing process until the nonstationarity effect of constant change in travel time of the earth hauling process begins to constrain the base mixing process approximately 20 hr into the simulation. The stage buffer (Statistics Collection Mechanism 2) following the base mixing process accumulates between one and three road sections from approximately 8 to 76 hr into the simulation.

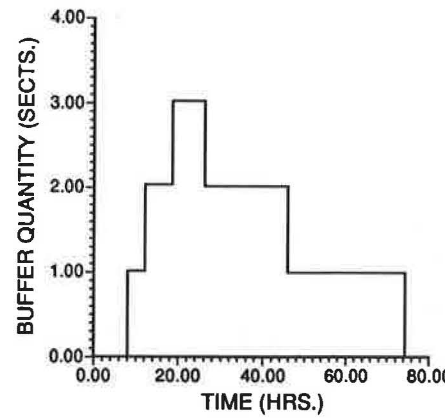
CONCLUSIONS

Previously developed planning techniques for linear construction operations based on the line of balance concept assume that process production curves are linear with respect to time. On the basis of the research performed, mean production curves for individual processes can be either linear or nonlinear. The use of simulation to generate the theoretical production curves and LOB for an operation is significant because simulation can provide realistic plots. These graphical plots can be used to easily determine what is wrong with an operation, to locate bottlenecks in the system, and to develop alternatives for improving the performance of the system.

In the cases analyzed, the phenomenon of production rate imbalance existed because the slopes of the individual processes had different characteristics. This production rate imbalance hindered production levels for individual processes and caused the buildup of partially completed production units



(a)



(b)

FIGURE 10 Buffer charts for the road construction case study: *a*, Statistics Collection Mechanism 1; *b*, Statistics Collection Mechanism 2.

in stage buffers between processes. An efficient method for improving the production characteristics of individual processes is needed to improve overall system performance.

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Development of a Construction Management System for the Southwest Freeway/HOV Lane Project

MICHAEL GIARAMITA AND BRAD WHITE

Innovative techniques to facilitate the construction of a fast track highway project are described. The techniques include extensive construction traffic sequencing, special specifications, and a customized critical path method scheduling system. Explanations of the methodology used to implement these items and the thought behind them are provided. Their application has been difficult at times, but is proving to be exceptionally successful. The Southwest Freeway/HOV Lane Project, located in Houston, is the single largest reconstruction project ever attempted at one time in the state of Texas. Construction began in August 1989 and is scheduled to be complete in December 1992, a 40-month duration. The project encompasses 10.6 mi of the heaviest-traveled roadway in the state; average daily vehicle volume exceeds 250,000. The estimated cost for this reconstruction is $200 million. A description is given of how the system came about. It covers the original goals and how the sequencing was laid out. Also covered are the hardware and software that were selected to help accomplish these goals. Customizations that were made to the scheduling software are described in detail. Preparation of the preconstruction schedules that provided information used in the specifications is also covered. The utilization of the system is also described. The organization of the project, the staff necessary to implement this system, and the details of utilizing such a comprehensive scheduling/management tool are covered. Examples of how the system is used to manage the work and prevent time delays are included. As of October 1991, the project was approximately 70 percent complete and 3 months ahead of schedule.

The Southwest Freeway (US 59), located in Houston, is the single largest reconstruction project ever attempted at one time in the state of Texas. Construction began in August 1989 and is scheduled to conclude in December 1992—a 40-month duration. The project encompasses reconstruction 10.6 mi of the heaviest-traveled roadway in the state; average daily vehicle volumes exceed 250,000. The current estimated construction cost is $200 million.

The project is divided into four segments (I–IV). Four contractors are working side by side to accomplish this reconstruction. There are 18 main-lane bridge structures on the project.

	Length (mi)	*Number of Bridges*
Segment I	2.7	4
Segment II	2.6	3
Segment III	2.6	4
Segment IV	2.7	7
Total	10.6	18

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Of the 11 main-lane bridges in Segments I, II, and III, 9 will be demolished and constructed from the ground up. Of the remainder, one bridge will be widened and overlaid, and one new bridge will be added. All bridges in Segment IV will be widened and overlaid with a 4-in. layer of concrete. Three of the existing seven bridges were raised 1 ft to provide additional clearance underneath them.

New frontage roads were constructed, adding as much as two lanes (four lanes total) in some areas and three lanes (five lanes total) at the major street intersections. The number of main lanes will basically be doubled, from 6 to 12 lanes. In addition, a high occupancy vehicle (HOV) lane will be constructed in the center of the freeway, with three T-ramp bridges providing direct access to park & ride lot facilities.

When the project is complete, more than 1.7 million yd^2 of concrete paving/bridge slabs will have been placed. All of the frontage road paving is 9 in. thick, main-lane paving is 13 in. thick, and bridge slabs average 7 in. This yardage does not include concrete used for foundations, such as bridge structures and drilled shafts; it includes only surface area yardage.

CONSTRUCTION MANAGEMENT SYSTEM DEVELOPMENT: MANAGEMENT PHILOSOPHY

Goals of the System

The construction management system (CMS) developed for the Southwest Freeway has several goals:

- Build the project on time (in 40 months),
- Evaluate progress of contractors,
- Protect project owners from unwarranted claims, and
- Refine system for future use.

These goals are being accomplished, and additional benefits are being discovered. One such benefit derived from the system is the ability to better negotiate with the contractor. The information contained in the scheduling system, especially the resource loading, makes it difficult for contractors to get by with unrealistic demands in negotiated settlements.

Construction Sequencing

The reconstruction of US 59 is being accomplished while US 59 continues to carry its already overloaded traffic volumes;

existing capacity (number of lanes) has not been reduced during the reconstruction. Volumes have dropped some but are still above 200,000 cars per day. The foremost concern of everyone involved with the project was how to accomplish the reconstruction while continuing to keep traffic flowing. At the same time, a goal was established to minimize the construction duration and inconvenience to the traveling public while providing a safe facility.

The design consultants produced more than 1,000 sheets of traffic control drawings to plan this goal. During the planning and drawing production phase, many believed this procedure to be overkill. The criticality of this seemingly excessive planning and these drawings is now being realized. Most of the large-impact construction problems have come from traffic management issues. The traffic control philosophy is presented in Figures 1a and 1b.

Each project segment is divided into three phases. In the first phase, the frontage roads were reconstructed. The main lanes and bridges on both sides of the freeway were widened in Phase 2. During Phase 3 the middle-of-the-freeway main lanes and bridges and the HOV lane and T-ramps are constructed. Because of the phasing, four large projects were each effectively broken into three smaller, more manageable projects of about 1 year in duration.

The completion of each phase provides improved traffic flow. Noncompletion of any of these phases meant delays to the traveling public. The delays were transformed into road user costs (costs associated with delays to the traveling public due to construction) and were estimated at over $450,000 per day. The cost for these delays was translated into liquidated damages and attached to the end of each phase. The liquidated damages are large: $15,000 per day for Phases 1 and 3, and $10,000 per day for Phase 2.

Why CPM Scheduling?

The traffic control drawings and phase requirements established the work flow. The only element missing is the time frame needed to accomplish the work. This is what critical path method (CPM) scheduling adds.

CPM is a derivation of program evaluation and review technique (PERT), which has its origin in operations research. CPM scheduling is a model that allows for simulation of real-world situations without resorting to real-world experiments. Models are, in essence, an imitation of reality.

CPM modeling constructs, on paper, each of the project segments piece by piece, developing tasks/activities, calculating durations (on the basis of resources) to achieve these tasks, and logically ordering them until the project is complete.

Once the traffic control or sequencing is established, the scope of work is developed. Applying CPM methodology to the traffic control scope of work/sequencing yields a schedule, or duration to construct the project.

Selection of Scheduling Hardware/Software: What Was Considered

From inception, it was decided to use a personal computer–based local area network in a central project office. A seven-station network was set up. For our file server, we choose a 386 25-MHz computer. It originally had a fast access 300-megabyte hard disk for storage. Because of the large scheduling and plot files generated and the desire to keep them on the file server, a larger 600-megabyte hard disk was installed. Ethernet cabling was used to connect the seven 386SX 16-MHz workstations.

To print and plot the various reports, several output devices were provided. For large plots, an E-size pen plotter is used. For A-size plots, a laser printer with a plotter cartridge is used. The same printer is used for tabular printouts. A laser printer capable of Postscript output is also on the network for producing reports and graphics.

It was recommended that the contractors use a 386-based computer with at least an 80-megabyte hard disk and that they purchase a D-size pen plotter. Another recommendation was for the purchase of a laser printer because of the many pages of output required to successfully use the system.

A high-end project management software project was selected. The software was selected because of its ability to handle a large number of activities and to be customized to meet the project's needs.

Software Customizations

There are basically two items in a CPM schedule that can be challenged: logic and activity duration. Logic can be simplified by using mostly finish-to-start relationships; the succeeding activity cannot begin until the preceding activity is completed.

However, the duration of an activity is more complicated. Duration of an activity is usually determined by the resources allocated to that activity. Resources include hours per day, productivity of the crew, and quantity of material to be installed. Amount and size of equipment also influence the duration.

Inaccurate durations are a typical problem with most contractor-supplied schedules. Often when schedules are developed, little attention is given to activity durations. Also, large chunks of work get lumped together into one activity.

Based on the Metropolitan Transit Authority of Harris County, Texas (METRO) specifications, support staff, together with the software vendor, customized the product to use resource quantities and production rates to calculate durations. In addition to the software vendor's customization, we have made system modifications, created special dBase programs, and written custom reports.

Without the activity resource information it is difficult to know what the contractor was thinking when the activity was originally planned/scheduled. The data documenting the duration of each activity are usually stored in one person's mind. By requiring the duration to be calculated, the contractor is forced to share assumptions and estimate information with the owner.

This information becomes an integral part of the schedule. Crew size, quantity of material to be installed, material production rate, and equipment are all stored in the schedule. The information documents the contractor's assumptions when the schedule was developed. Resource management is the key to constructing a project on time, and for the contractor it will determine whether money is made or lost.

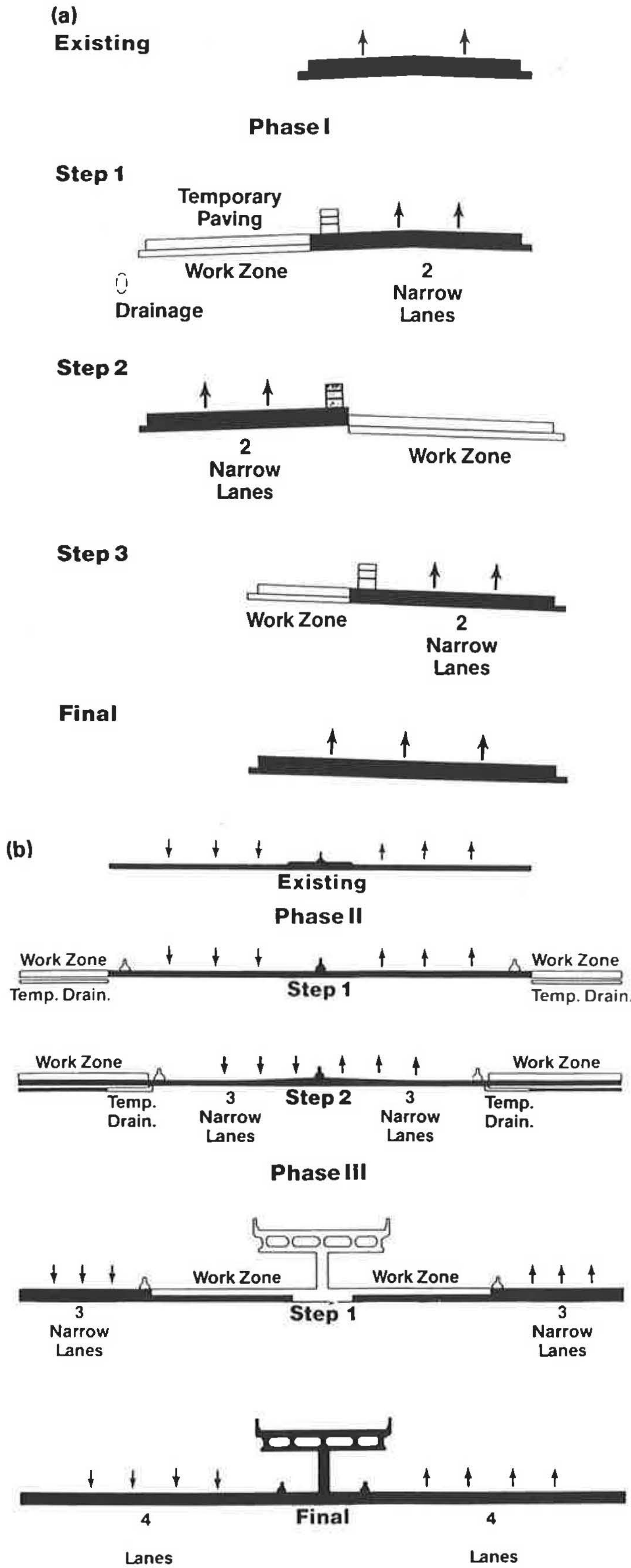


FIGURE 1 Traffic control phasing: *a*, southbound frontage roads, Phase 1; *b*, main lanes/HOV lane, Phases 2 and 3.

Figure 2 shows the information required and how it is used to calculate duration. In this example, concrete paving is the lead resource, and concrete paving crew is the labor resource.

Global changes can also be made. For instance, if one wanted to change the hours worked per day for all activities not started and recalculate the schedule, this can be accomplished with a few keystrokes.

A side benefit from this calculation is the estimated work hours required to complete each activity. With work hour information, S curves were developed for the entire project and for individual resources. Work hours by activity are useful because they indicate the intensity of activity. In other words, you can determine highs and lows in the schedule, which aids in leveling. An example of a work hour S curve is shown in Figure 3.

Given: Concrete paving Ln. 4 & 5 Sta.306+00--Sta.314+95 IB (22 ft wide)

Quantity = 19,690 sf or 2,188 sy.

Lead Resource is Concrete paving, which has a productivity rate of 0.10 manhours per unit.

Labor Resource is concrete paving crew of 22 people.

Hours worked per day is 10.

Calculated:

$$\frac{\text{Material resource} * \text{Production rate}}{\text{Labor crew size} * \text{Hours worked per day}}$$

$$\frac{2{,}188 * 0.10}{22 * 10}$$

Duration: 1 day

FIGURE 2 Duration calculation example.

This curve represents one phase of one project segment. A window is formed by lines representing the baseline early and late start dates. The backup data for each line is the accumulation of work hours for each activity spread between the start and finish dates. The earned value line is derived by spreading the work hours between the actual start and finish. The projected earned value line uses the dates calculated in the schedule.

Figure 4 is an example of the activity maintenance screen. It has fields to input the information needed to calculate the activity's duration. Once the information is input, the duration is automatically calculated.

Preparation of Preconstruction CPM Schedules

To establish a duration during which the project could be constructed, preconstruction CPM schedules were developed. When a construction contract is prepared, the Texas Department of Transportation (TxDOT) assigns the duration (usually in calendar days) in which the project is to be constructed. On the basis of past jobs, TxDOT wanted to allow 5 years—60 months—to reconstruct the Southwest Freeway. METRO felt it could be accomplished in 3 years, or 36 months.

On the basis of the traffic control sequencing, work activities were developed for each traffic control plan (TCP) phase

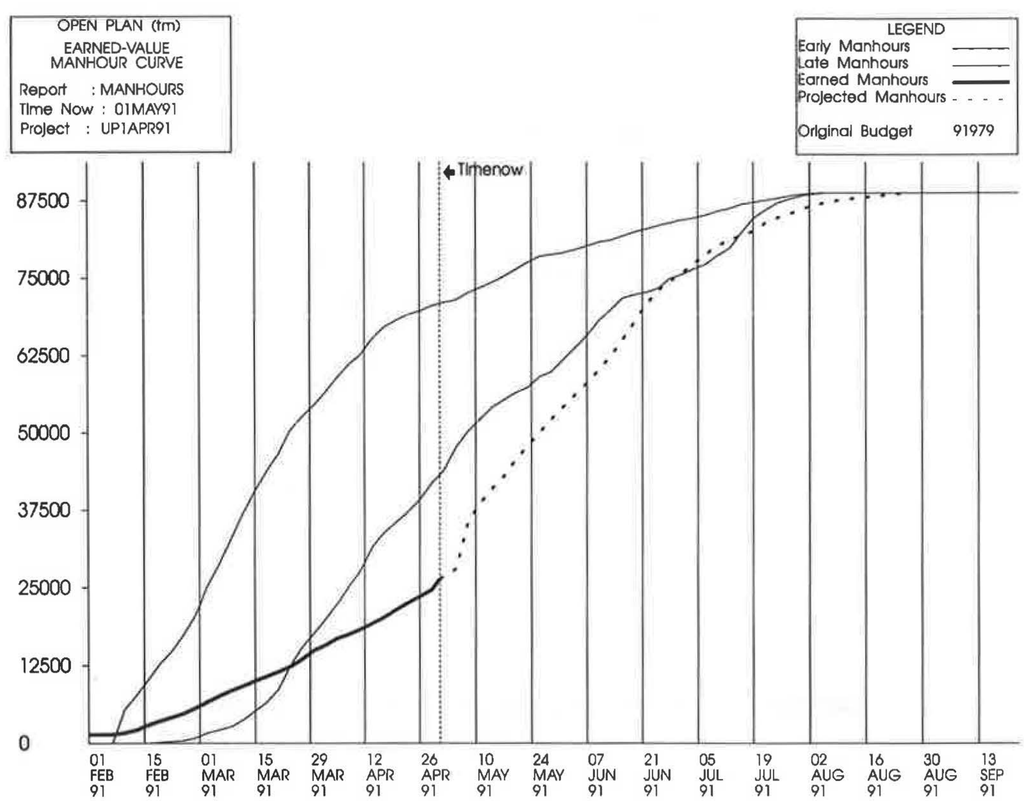
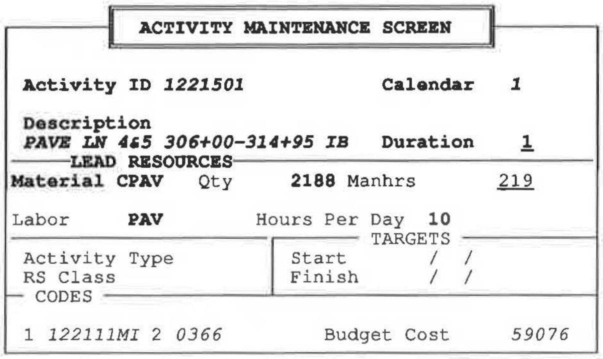


FIGURE 3 Work hour S curve, US-59 Southwest Freeway, Segment 1.


ACTIVITY MAINTENANCE SCREEN

Activity ID *1221501* **Calendar** *1*

Description
PAVE LN 4&5 306+00-314+95 IB **Duration** 1

LEAD RESOURCES
Material CPAV Qty **2188** Manhrs 219

Labor **PAV** Hours Per Day **10**

Activity Type
RS Class

TARGETS
Start / /
Finish / /

CODES
1 *122111MI* 2 *0366* Budget Cost *59076*

Bold items are input and used in duration calculations.

CPAV is the material resource (production rate of 0.10 mh/sy).
PAV is the labor resource (crew of 22).
Qty is the quantity of the material resource (2,188 sy).
10 is the hours per day worked.

The underlined items are calculated given the above information.

Duration is the calculated length of this activity in days (1 day).
Manhrs is the total manhours calculated for this activity (219 mh).

The italicized items were also input but were not used in the calculations.

FIGURE 4 Activity maintenance screen.

and step. The activities were resource-laded with quantities of material to be installed and the manpower needed to install them. The system used this resource information, along with production rates and planned hours per day, to calculate the activity's duration. All activities were linked together in a logical sequence of progression and applied against a preselected calendar, yielding a time frame to complete the project.

Once the basic model was constructed, "what-if" games were developed by changing one variable at a time and noting the results. For example, one scenario changed the hours per day from 10 (one shift) to 16 (two shifts). The results of this change were calculated in less than 30 min. Many "what-if" games were played; in fact, it got out of hand. Three scenarios were finally settled on: a regular work schedule (5 days/week, 10 hr/day), a moderate work schedule (5 days/week, 16 hr/day) and an accelerated work schedule (7 days/week, 16 hr/day). TxDOT selected the moderate work schedule, which yielded a total construction duration of 40 months, including contingencies for items such as bad weather. The schedules were presented to the Association of General Contractors, and the project duration met with its tacit approval.

The following list gives some of the direct and indirect benefits of reducing the Southwest Freeway construction duration from 60 to 40 months. These benefits are a direct result of the model employed.

1. As mentioned previously, road user costs were estimated at $450,000 per day for this project. This cost is based on a study performed by a traffic research institute. They used several commonly accepted methodologies to arrive at this amount. Translating this daily cost into a lump sum to reflect the 20 months (600 day) saved yields $270,000,000.
2. TxDOT and METRO staffs will only be required to be on the project for 40 months, not 60, thus freeing staff for other projects.
3. People who have to travel the freeway will be inconvenienced for just 40 months, rather than 60 months.
4. Merchants along the freeway will not have to endure a 5-year construction duration, lessening their hardship.

The list goes on. CPM modeling provided sufficient evidence to convince TxDOT to reduce the construction duration. TxDOT usually uses a conservative estimate when setting the duration of a construction project, since they rely on experience, which can be subjective. The CPM model provided a more objective and scientific approach to setting the project duration. On this project the contractors were required to construct the project in 1,200 days.

The CPM model example, in terms of benefits derived, is as comprehensive a model as could be constructed [saving more than $100 million, half of the estimated project cost (at least on paper)]. It basically depicts all the "right" elements that make modeling a successful endeavor. The cost of constructing this model was approximately $100,000, which includes METRO labor and purchase of the microcomputer, plotter, scheduling software, and programming and consultant services. The total estimated project cost for the Southwest Freeway is $200,000,000. The ratio of cost to construct the model to total estimated project cost is 0.05 percent. The ratio of cost to construct the model to the potential road user delay costs saved is 0.04 percent.

The CPM employed to construct the model is, as far as we know, the most precise method to simulate a situation such as this. This method of predicting events over time and total project duration is widely accepted in industry today.

There are many advantages for using models in making policy decisions. Simply put, these advantages are a result of the model's ability to simplify and predict consequences faster, cheaper, and safer than actually implementing each alternative or making an educated guess about which one is correct.

The durations calculated in the preconstruction schedules were used to substantiate the length of time needed to perform each traffic control phase. In other words, they were the basis on which each of the four project segments' duration was based.

Preparation of Specifications: Important Factors To Consider

Specifications and special provisions are included with design drawings to instruct the contractor to perform the work in a particular manner. They specify items that cannot be stated on the drawings or are better stated elsewhere. On TxDOT projects, and in most states, if not all, specifications and special provisions take precedence over the drawings. In other words, if there is a conflict between the specifications and the drawings, the specifications rule.

Specifications and special provisions of interest in the management of this project include (*a*) description of project, scope of contract, and work sequence, which generally describes the project scope of work and, in writing, details what is to be accomplished in each traffic control phase/step; and (*b*) prosecution and progress, which is a catchall for telling the contractor how the project is to be constructed. This is where specifications for the CPM scheduling system appeared. Also included in this section are the time requirements for the project and the liquidated damages clause.

Preparing a management specification is arduous. Many people must be interviewed and their objectives considered. People from several organizations were interviewed, including METRO, TxDOT, the Attorney General's office, various contractors, and the Association of General Contractors. All had different ideas on what they wanted to see in a management specification.

The specification dictated the common scheduling system to be used, how to establish activity numbers, coding of fields, and resource requirements. In fact, the specification also stated how to name the monthly update files submitted by each of the four contractors. The system was developed with much thought to afford the maximum flexibility in sorting and selecting data and to ease downstream management of data. Figure 5 shows an example of how activities and code fields were used.

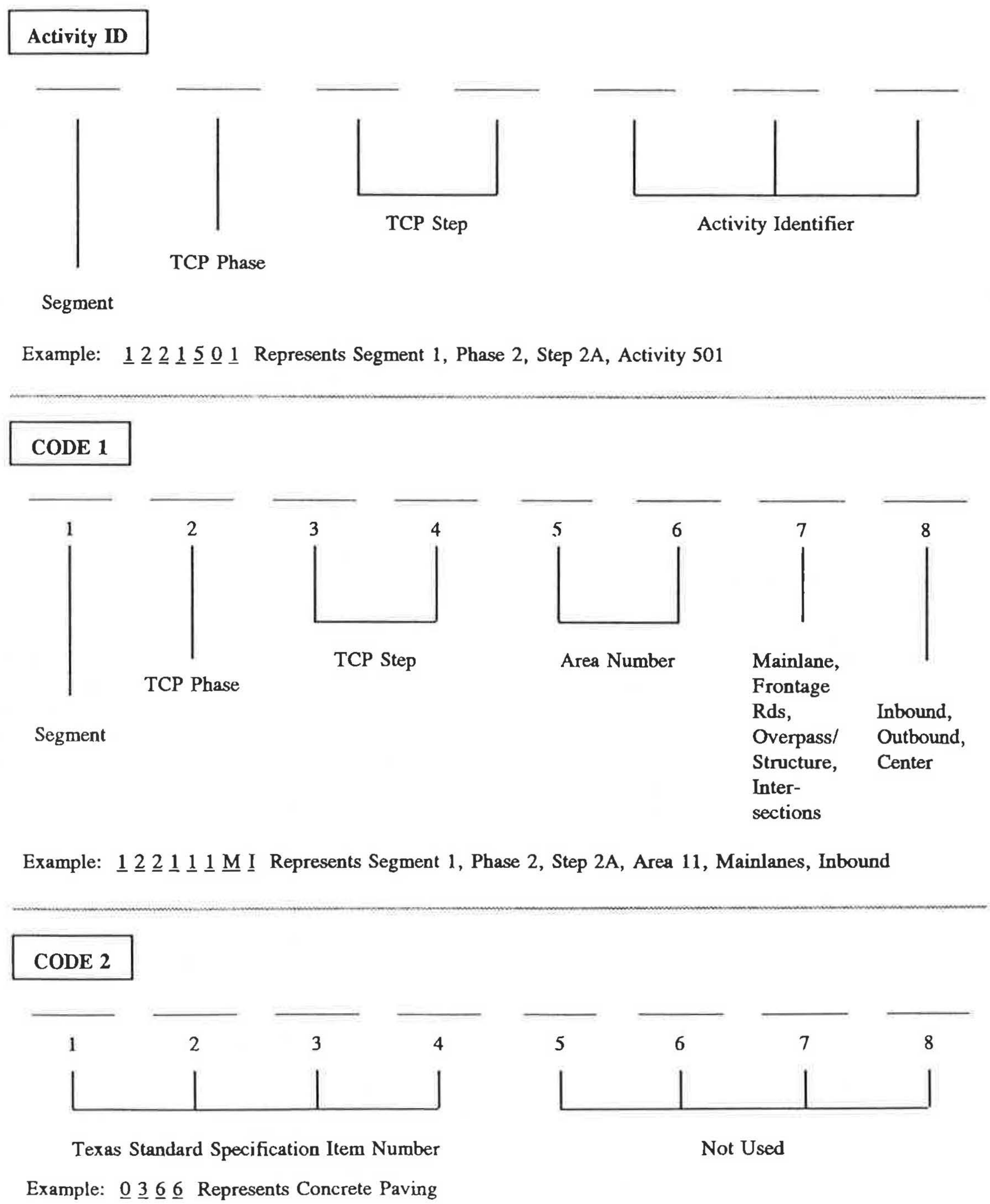


FIGURE 5 Coding field structure.

Some were in favor of what was being done, and others were skeptical. There were problems on other construction projects where CPM schedules were used because these projects had less-than-desirable results. Some people blame the management specification for these problems. We blame the lack of some specifications and the lack of attention paid to monitoring the work.

Specifications are like a set of instructions, or a recipe. The truth is you cannot prepare a specification and expect that to be the end. To make a cake you have to buy the ingredients, mix them together, and bake them. If you fail to complete each step correctly, the results will not be what you expected.

The specification only establishes the ground rules. The specification must be monitored for compliance, and staff must be dedicated to enforcing the rules established.

The Simpler Said, the Better

The most important lesson learned is to prepare specifications in the native language where they will be applied. In Texas they should be prepared in English. Not a lawyerese version of English, but good old plain English. The simplest, most straightforward way to say it is the best way to say it. Eliminate all the "whereto's" and "whereas's." Say what you mean in simple, concise, proper English.

One person interviewed said that a major problem he was aware of on one job was that the contractor fell behind schedule and began working 24 hr/day, 7 days/week to catch up. TxDOT was not staffed to work these hours. It resulted in burnout. On the Southwest Freeway, a specification states, "The Contractor can work between the hours of 6 am to 11 pm unless he obtains written permission from the Engineer." This simply written specification eliminated ambiguity.

Another problem TxDOT was experiencing on other projects was that contractors typically would move on to TxDOT right-of-way and begin tearing it all up. The contractors started working on the frontage roads, the main lanes, the major intersecting streets, everywhere they could, all at one time. To say the least, this had a major impact on the traveling public. These were the projects that never seemed to get finished.

Again, a simple specification was written stating that "the contractor could not begin a succeeding phase of work before completion of a preceding phase without the written permission of the Engineer." Simply put, this specification controlled where the contractor could work. It forced him to organize his work.

The key point here is, tell the contractor what you want and do not want him to do, and say it in the simplest terms—and most of all, tell him before the contract is signed.

CONSTRUCTION PHASE

Project Organization

The contractors are under contract directly to TxDOT. TxDOT manages and inspects all work and ensures compliance with the contract documents.

METRO is in a support role to TxDOT, providing construction management services including scheduling, claim prevention and review, design support services, and preparation of construction status reports.

This organization works well. There is a clear division of responsibility. TxDOT gives all direction to the contractors. METRO supports TxDOT in its areas of expertise.

METRO has a staff of 4.5 people assigned to this project (the 0.5 person, the manager, divides his time between design and construction responsibilities). There are two project managers, one construction engineer, and a project secretary. To accomplish METRO's scope of work, a project manager is assigned to two project segments. This project manager, along with the assistance and experience of the senior construction engineer, reports on the project's status and works to resolve problems that arise.

TxDOT has a staff of approximately 70 people, including 12 administrative and 58 inspection staff.

Review and Approval of Contractor Schedules

By specification, contractors are required to submit a resource-loaded CPM schedule. Resources include the number of workers, types and number of pieces of equipment, and material to perform the work for each activity.

Through the flexible report-writing capability of the scheduling software, reports were generated that summed each of the resources by TxDOT standard specification item numbers. These quantities were compared with the planned quantities to determine whether the contractor considered all quantities to be installed (scope of work).

Even though we had all the capabilities for writing and producing many different types of reports, the process of reviewing more than 14,000 activities almost killed us. We had to bring in outside consultants to help in this review. However, this was known beforehand, so consultants were under contract and ready to begin their review on a moment's notice.

Monitoring the Work

With a staff of three professionals, all activities in the field are monitored weekly, sometimes two to three times a week. In fact, at any time the scheduling software can provide up-to-date information about the status of any of the projects. The staff converses on the schedule activity level, so everyone is on the same page.

The projects that are, or appear to be, behind schedule are monitored more closely. Activity update reports are produced (see Figure 6) and updated two to three times weekly. Updates include information about resources on each activity (number of workers and pieces of equipment) and a description of what work is being performed. This information is compared with the contractor's planned information, located on the top of the form. This form is printed directly from the information stored in the scheduling system, without further modification.

Date-stamped progress photographs also are taken two to three times weekly. Along with the completed progress sheets, they depict the activities' status or lack thereof.

As discussed previously, a project manager is assigned to two project segments. The project manager and the senior

OPEN PLAN PAGE: 1

ACTUP Activity Update Report REPORT DATE:09SEP91

UP1FEB91 US - 59 SOUTHWEST FREEWAY: SEGMENT 1 TIME NOW:01MAR91

1221501 PVAE LN 4&5 306+00-314+95 IB Org Dur = 1 Rem Dur = 1 Total Float = 0

Budgeted Cost = 65640 Manhours = 219 Code 1 = 122111IM Code 2= 0366
Material Resource Code = CPAV CONCRETE PAVING Productivity Rate = .10000
Total Quantity = 2188 SY Remaining = 2188 SY

BASELINE Start 08MAR91 Finish 08MAR91 ACTUAL
EARLY Start 23MAY91 Finish 23MAY91 LATE Start 29JUL91 Finish 29JUL91

Resources
PAV PAVING CREW Crew Size = 22

Date	OBSERVATIONS

FIGURE 6 Activity update report form.

construction engineer provide the necessary input to determine the status of the project and provide alternatives to keep the project moving forward.

CPM Schedule as a Management Tool

Using the Schedule To Prevent Delays

Different industries use different methods for communicating ideas. In the construction industry, CPM schedules are the most effective method for communicating what the contractor plans to accomplish and when the contractor plans to accomplish it.

The information in the schedule gives advance notice to the owner of when and where the contractor plans to work. For example, if the owner has not acquired all the property or has not had all the utility adjustments made (this does not happen in Texas), the CPM schedule will tell the owner when the contractor is planning to work in these areas.

It is up to the owner to use this information to keep ahead of the contractor, clearing the way for the contractor and preventing delays. It takes at least two to communicate, one to talk and the other to listen. The information in the CPM must be updated and reviewed constantly in order to establish the two-way communication.

On one of the project segments the TxDOT resident engineer used the work hours curve (see Figure 3) to support his "gut feeling" that the contractor was behind schedule. The resident engineer believed that he was behind schedule because of a lack of resources (workers and equipment). Several letters were written to the contractor, supported by the resource information extracted from the scheduling software and actual head counts, demanding that more resources be assigned to the project.

Utilizing the Schedule To Prove or Disprove Claims

The CPM schedule is a powerful tool in proving or disproving construction claims. A construction project is riddled with negotiations. People on both sides are always looking out for their own best interest. The CPM becomes invaluable for negotiating both time and money.

However, it is a two-way street. If work is disrupted and this work is on the critical path, the contractor is probably due time if, of course, he is not able to work on any other critical path items.

A highway project is linear in nature. Many similar activities can be worked on simultaneously. Therefore, a contractor delayed in one area could probably be allowed to work in another area performing similar work.

This is not always true and can be analyzed through the CPM schedule. If the delay does not affect the critical path, float is used up until the delay is resolved. On this project, float is not for the exclusive use of either the owner or the contractor. It is for use by whoever uses it first.

The ability to use resources as the basis for activity durations created a third dimension for managing the project. For example, if work is not proceeding as scheduled in one area, one could analyze not only the time elements but also how the time elements were originally derived, the production rates used, and the type of equipment used. All this information gives the insight needed to correctly and completely analyze a schedule. There have been several instances where the resource information has been the key item in disproving a claim.

For example, one of the contractors stated he was submitting a time impact on his Phase 2 work because of delays in relocating utilities. After a thorough analysis it was determined that the delay was really associated with the construction of retaining walls, or the lack thereof. The contractor had this activity staffed as indicated in his schedule; however, there was a flaw in the production rate. The production rate was a factor of three to four times less than the other contractors. This resulted in durations of one-fourth of what they should have been. This information was discussed with the contractor and his claim was never submitted.

Using the Schedule To Plan Owner-Required Resources for Inspection of the Work

Because of the sort and selection capability of the scheduling software, planned and actual quantity curves can be produced that indicate intensities of operations. A traditional CPM schedule tells you when an activity is to start and stop. The system developed on the Southwest Freeway tells you resource intensity, enabling the owner to plan staffing more precisely.

This information allows TxDOT to know when, what type, and how many people are needed for the inspection. Optimization of the owner's resources is accomplished more precisely using this method.

What the Schedule Will Not Do

A CPM is like any other system; if left unattended, its results will be less than desirable. CPM schedules require constant nurturing.

CPM provides you with a communication of how the job is to be built. It is up to human resources to make sense of what is being communicated and how to best use the information. CPM alone does not make one job better than one without CPM. Without a dedicated staff that understands CPM and the project being constructed, the effort is token at best.

CPM will not control the project unless the CPM is controlled. A plant without water will eventually die. CPM without constant attention will also lead you down a primrose path. The old "GIGO" rule applies: garbage in—garbage out.

What makes a project successful is thorough planning before and during execution. One must anticipate problems and resolve them before they become problems. CPM gives you the ability to thoroughly plan your work. However, as we all know "things happen" during the construction phase that you hadn't planned for. CPM makes it easier to analyze downstream effects of these changes and allows one to "crystal ball" what will happen.

CMS Working Together—CPM Schedule, Specifications, and Dedicated Staff

The CPM schedule, the specifications, and a well-founded organization have all worked together to form a synergic bond. Without any one of these elements the outcome would be less desirable. As a result of this bond, unexpected benefits were derived from the CMS.

One of the most powerful management tools resulting from the CMS was the ability to better negotiate time extensions with the contractors. The specifications established milestones for three distinct phases. The milestones were set up as "finish on" dates. The specification, as stated previously, said that "the contractor could not begin a succeeding phase of work before completion of a preceding phase without the written permission of the Engineer." When a contractor began work in a succeeding phase before completing the work in the current phase, we were in a much better position to negotiate time extensions.

For example, when the Segment III contractor was in Phase 1 (frontage road reconstruction), he began prosecuting Phase 2 work with the engineer's permission—approximately 8 months early. After 5 months of working in Phase 1/Phase 2 simultaneously, there was a field change to the drainage system

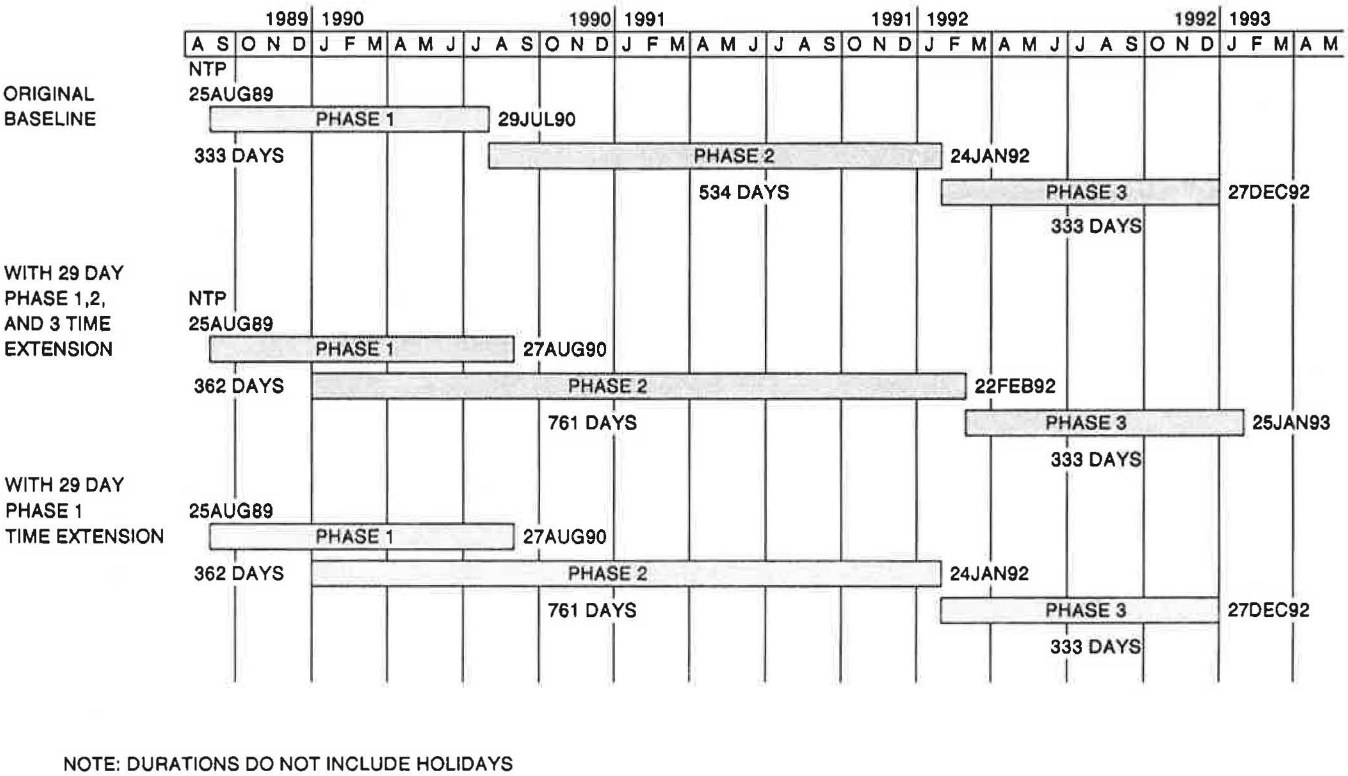


FIGURE 7 **Results, Segment III proposed time extension.**

being completed in Phase 1. The contractor asked for a 29-day extension in Phase 1, Phase 2, and Phase 3, which would have extended the end date of the project.

The contractor was awarded 29 days in Phase 1 only. As the basis of this decision, we pointed out that he had already worked 5 unscheduled months on Phase 2 and had another 3 months of Phase 2 work he could accomplish while still in Phase 1. The CPM verified that the contractor had earned more than the 29 days of Phase 2 work while in Phase 1. The contractor was reminded that it was a privilege, not a requirement of the contract, to allow him to work in a succeeding phase. He was also told that this privilege could be revoked at any time. Figure 7 shows the results of time granted.

The contractor's request for a time extension in all three phases was reduced to a time extension in Phase 1. A simple concept became a powerful management tool. The integration of the CPM schedule and the specification provided the ability to accomplish this.

LESSONS LEARNED—THINGS THAT MIGHT BE DONE DIFFERENTLY

Basically, we would do nothing different. However, some operational refinements could be made to the specification. When a comprehensive management specification is written for a project, the owner, as well as the contractor, must have experienced dedicated staff to make it work. It is a shared responsibility, and the degree of its success is measured on both sides; it's not a one-way street.

As of the writing of this paper, there have been no construction claims. In the event of future claims, the comprehensive information provided by the system should assist both the owner and the contractor in effectively resolving these disputes. The project is approximately 70 percent complete and is 3 months ahead of schedule.

Publication of this paper sponsored by Committee on Construction Management.

Taking a Computer to the Construction Job Site

HOSIN LEE AND GERALD E. JOHNSON

The feasibility of using a portable computer at the construction job site is investigated. By the use of a portable computer, the workers can have access to a large amount of data and critical management information. The availability of a portable computer would allow the management staff in the office to better communicate with the foreman, the foreman to more effectively manage construction projects, and the inspector to more accurately inspect construction quality. Two approaches to taking a computer to the construction job site are discussed: a pocket handheld computer and a voice-activated, head-mounted computer. Each is evaluated for capabilities and limitations. Currently, a wide variety of portable computers is available to suit the needs of the specific application. However, there are not enough software packages available for use on portable computers. Additional software development effort on portable computers would make them more useful at the construction job site. These portable computers are tools to help collect information for improving the existing management process, increasing awareness by construction workers of construction quality concerns, and promoting more scientific methods of improving various construction operations.

As more decisions are made at the construction job site, the amount of information needed at the job site is increasing. These important decisions are often made at the foreman level. Therefore, the foreman becomes a key person in improving construction productivity. The foreman, managing the construction crew, currently needs, at a minimum, a pocket calculator to convert measurement units, calculate volumes of work performed, and so forth. The question addressed in this paper is whether it is necessary to take a more sophisticated computer than a pocket calculator to the construction job site. Many papers have emphasized the use of computers in the field office environment, but not at the job site level by the construction workers.

In the past, a number of studies have identified ways to improve construction productivity, but they are short of recommending a tool to improve it (*1*). The objectives of this research are to investigate the uses of computers at the construction job site, identify available computer hardware and software, and evaluate them for possible application in the construction job site environment.

COMPUTER NEEDS AT CONSTRUCTION JOB SITE

The ever-increasing amount of information needed at the construction job site, along with the availability of smaller computers, has created a demand for computers at the job site. There are certainly construction operations that, if improved by use of computer, would result in savings in both time and money.

One of the most common problems in construction operations is the communication gap between various parties—project engineers, superintendents, foremen, and construction crews. This communication gap can be greatly reduced if all parties use the same procedures such as construction scheduling methods, measures of construction productivity, and so forth. These measures of construction productivity, for example, have been available only to management staff in the office environment. Such valuable information was not available to field workers because of their limited access to the computer and the difficulties of verbal communication between office and construction crews.

Although laptop computers are becoming commonplace in many industrial applications, they can still make quite a stir when they are used at the construction job site. A number of so-called palmtop computers are available in the market. They are handy, light, small, and inexpensive. They are about the size of a checkbook, so they can easily be put into the pocket. Another class of computers that can be used is a voice-activated, head-mounted computer with a small computer screen attached to the head. This would make an ultimate portable computer with two hands free for other functions.

CURRENT USE OF COMPUTERS IN CONSTRUCTION

Recently, new computer applications and technologies have been given the utmost priority in construction research. New directions in computerized construction research have been identified as (*a*) projectwide data base and communication, (*b*) knowledge-based expert systems, (*c*) simulation of construction activities, and (*d*) robotics (*2*). Most computerized construction research so far seems to emphasize research tools more than the real problems at the construction job site.

Construction companies are actually decentralizing their computer resources by putting personal computers at the field office. One study reported that the decentralization permitted greater flexibility in job cost control and construction scheduling applications (*3*). It also indicated that there were training needs for field personnel regarding the use of the computer.

Automated inventory control at the construction job site using a bar code technology has been proposed (*4*). Inventory control of construction resources such as materials and equipment can be automated using a bar code label. The label can

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be read by the bar code scanner. A limited set of job site activities can also be identified using an activity identification sheet of corresponding bar codes. Bar code technology is becoming popular as a means of collecting construction field data, but it may require a number of expensive hardware elements, such as scanner, remote reader, and concentrator, let alone lots of bar code labels.

Recently, a knowledge-based expert system was developed on a desktop computer to provide advice to inexperienced inspectors concerning how to identify and correct deficiencies in the asphalt pavement construction operation (*5*). A great area for an expert system application on a portable computer appears to be to help inexperienced inspectors at the road construction job site.

HAND-HELD COMPUTER

Recently, smaller computers such as laptop and notebook computers made headlines in many computer magazines (*6–8*). Much of the functionality of these computers is now available on even smaller palmtop or hand-held computers, which can slip into the pocket (*7*). The size of hand-held computers is in the range of checkbooks and VHS tapes. They look like pocket calculators but act like desktop computers. There are a number of manufacturers of such pocket hand-held computers in the market, including SHARP Wizard, Psion Organizer, Atari Portfolio, Hewlett-Packard 95LX, Poqet PC, CMT MC-Series, National Datacomputer, and so on.

The reduction in the size of computers was accomplished because of a miniaturized PC-compatible motherboard with performance about 2.5 times that of an IBM XT (*8*). There is much variation among different hand-held computers in size, functions, and so forth. This paper does not evaluate each hand-held computer for its capabilities, but evaluates hand-held computers in general for construction job site applications. A detailed evaluation report on a specific hand-held computer can be found in a computer magazine (*8*). One study evaluated various field inspection methods for collecting pavement distress data and concluded that hand-held computers are relatively light, inexpensive, and easy to use (*9*). The general capabilities and limitations of hand-held computers are summarized as follows (*10*).

1. The small keys on most hand-held computers are not as easy to use as those on larger desktop computers. Entering information into hand-held computers is very awkward. They should be used for tasks that do not require much typing. The small screen can display up to 8 lines and 80 columns.
2. Most hand-held computers can be connected to a desktop computer. The hand-held computers support serial communications, so that information can be transferred between them and desktop computers in the office. Computer programs can be created on any computer and downloaded into hand-held computers.
3. Some hand-held computers have their own programming language and removable mass storage. Therefore, an application program can be written, compiled, and stored in an EPROM that functions like a disk drive. Peripheral devices such as printers, bar code readers, magnetic card readers, and modems are available for certain types of hand-held computers.
4. Quite a few hand-held computers are general-purpose computers for which a wide variety of software and hardware is available. In general, hand-held computers have slower CPUs and less RAM than desktop computers. The battery on some models may not last long enough for extended use outdoors.

The first requirement in the use of computers at the construction job site is to select the hand-held computer that best fulfills the needs of the application. Factors to consider when selecting a hand-held computer are durability, RAM and EPROM capacity, operating system and DOS compatibility, communication characteristics, and cost.

Several hand-held computers are available that would suit specific application needs. However, hand-held computers need more commercial software packages, the availability of which would make hand-held computers more attractive. Currently, a number of general software packages are available for the hand-held computer, including spreadsheets, data base management systems, advanced calculator, appointment/telephone book, file manager, communications programs, and so forth. However, not many software packages are available for hand-held computers for specific applications such as the construction job site (*11*).

ON-SITE SOFTWARE PACKAGE

The On-Site software series is developed by On-Site Technologies. It is a simple construction management tool for foremen at the construction job site. All programs were written in BASIC and are available on SHARP pocket hand-held computers. The structure of the program is simple, and the use of the program is easy. The objectives of the On-Site software package are to assist the foreman in determining actual costs and variances and in identifying delays and extra costs, to tell the crews how to improve their performance, and to give superintendents objective criteria for cost improvement awards.

Their simplicity allows the programs to be easily adapted by the foremen. The foremen can be guided through the program by answering mostly yes or no questions. The On-Site software package is shown in the Figure 1. The current On-Site software package includes functions such as performance audit, daily log, and cost analysis. On-Site software is intended to provide a foreman with the tools needed to better manage construction operations. The use of On-Site software, in general, involves five steps (*12*):

1. The estimated quantities and costs of the work to be performed are loaded into the On-Site software by a superintendent.
2. The actual cost of productivity is computed from job site data input by a foreman and compared against the estimated unit cost after the first phase of the work.
3. The foreman and crew answer a series of questions regarding conditions that might have affected productivity such as weather, safety, crew size, and so forth.

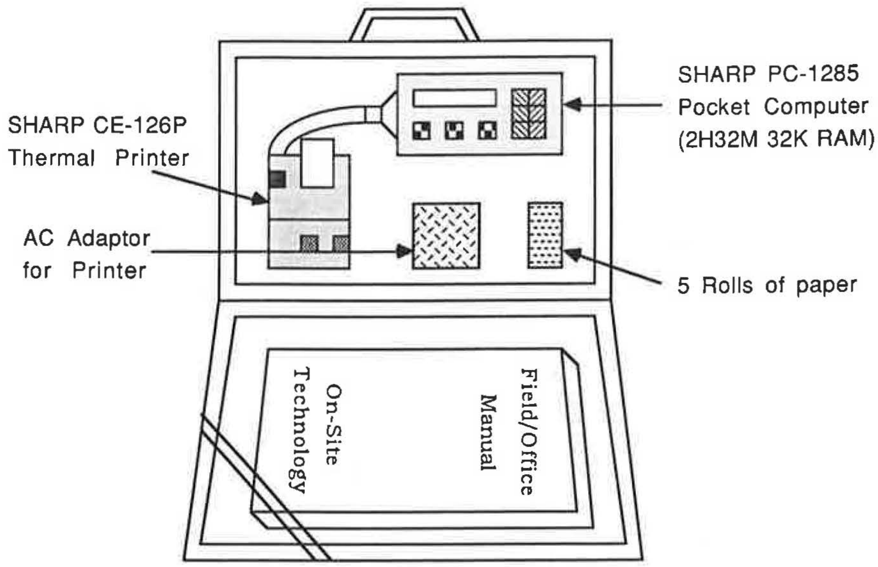

FIGURE 1 On-Site software package.

4. The foreman repeats Steps 2 and 3 after each day's work. The actual unit cost is compared with the one estimated by the superintendent.
5. The foreman prints out the actual unit cost with job site conditions and sends it to the superintendent for a feedback resolution of delay factors and a basis for recognition and reward.

A number of advantages can be realized by using the On-Site software package: establishment of specific performance goals, immediate awareness by the crew of its performance, increased interaction between office and job site, reduction of labor costs with increased productivity, and elimination of excessive paperwork.

The limitations of the On-Site software package are as follows:

1. Each contractor has a different way to manage construction activities, which may require customization of the software.
2. Use of hand-held computers with small screens and keys could be a nuisance to some foremen.
3. The capabilities of the current version of the On-Site software package include only limited areas of construction management, such as daily log, cost analysis, and performance audit. Additional functions should be added in other construction management areas, such as equipment inventory, short interval scheduling, change order/estimator, and inspection.

VOICE-ACTIVATED HEAD-MOUNTED COMPUTER

Hand-held computers have an inherent limitation: users have to use hands to hold them. One solution is to use a voice-recognition system with a computer screen hanging in front of the eyes. The first head-mounted computer was developed by NASA's Ames Research Center. It developed the Virtual Interface Environment Workstation, a wide-angle, head-mounted, stereoscopic display system that the operator's voice, position, and gestures control. Two disadvantages to this headset approach are as follows (*6*):

1. The user is tethered to one place.
2. It is very complicated to switch back and forth between different tasks if the users have to take off the headset every time they want to see something outside.

To reduce these limitations, a new head-mounted device was developed to show two-dimensional display to one eye while the other sees the real world. This device, called "Private Eye," a tiny computer screen, was developed by Reflection Technology. Private Eye weighs 2.25 oz and produces a 720- by 280-pixel display in a viewing window less than 1 in. square. It displays 280 lines with 720 columns (*13*). Private Eye allows users to work at other tasks while viewing important data such as construction schedules. By making displays more portable and less obtrusive, more areas, including construction job sites, become accessible to computers.

The first portable computer that can be worn as a helmet, headset, or work vest, called CompCap, was recently introduced by Park Engineering, Inc. (*14*). A schematic diagram of the CompCap unit configuration prepared by Park Engineering is reproduced in Figure 2. CompCap uses a Private Eye display device with voice data entry system and memory card interface with belt-mounted drive. It uses a voice recognition system called VMKEY developed by Convox, Inc., which allows the user to speak to the computer through a microphone. Convox states that this computerized voice recognition system remains an unreliable technology because of uncontrollable variations in the way that normal speech is produced in an uncertain and noisy acoustic environment (*15*). A special microphone may be used to suppress noise in a typical construction environment.

The CompCap computer is DOS-compatible, so it can be used to run any DOS-compatible software package. The

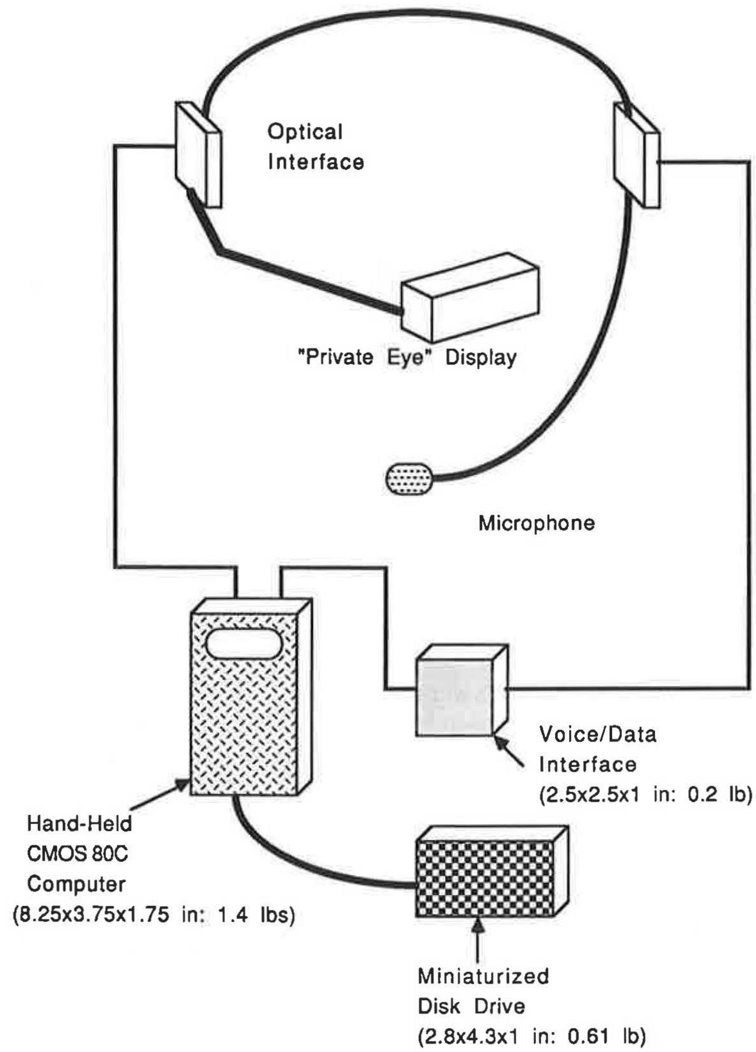

FIGURE 2 Configuration of CompCap ergonomic computer.

CompCap unit can be used at the construction job site for more detailed instructions and graphic displays for construction scheduling and inspection. For example, the memory joggers from the inspection guidebook (*16*) can be recalled with appropriate graphics using CompCap to help inspectors refresh their memories for specific inspection tasks. Since the CompCap unit was just released in 1991, no software packages are available for use at the construction job site using CompCap.

SUMMARY AND CONCLUSIONS

The advent of smaller computers with greater capabilities has motivated the authors to investigate the feasibility of using a computer at the construction job site. Although computers have been used extensively in the office environment in the past, the potential of using computers in the construction job site environment has just begun to be realized. The construction job site is usually an outdoor and noisy environment, and the prospective users of a computer at the construction job site probably never used a computer in the past.

By the use of a computer at the construction job site, the construction workers can have access to a large amount of data and critical management information. The availability of a computer would allow the management staff in the office to better communicate with the foreman, the foreman to more effectively manage the construction project, and the inspector to more accurately inspect construction quality. For example, a foreman who notices any work delays can correct the problem instantly instead of waiting until the labor productivity report is generated next day or even next week. This will improve construction productivity.

Various portable computers were developed and used by other industries such as utility metering, automobile renting, and manufacturing operations. A wide variety of portable computers is currently available to suit the specific needs of the application at the construction job site. This paper presents two approaches to taking the computer to the construction job site: pocket hand-held computers and voice-activated, head-mounted computers. Hand-held or head-mounted computers can greatly enhance the availability of critical information at the job site level, which would eventually improve construction productivity.

Significant demand seems to exist for such portable computers at the construction job site. However, not enough software packages are available for use on portable computers at the construction job site. Additional software development would make portable computers more useful at the job site. A customized development effort may be needed for each contractor, because construction operations at the job site would be different for various contractors.

Portable computers cannot replace the current construction management or inspection process currently existing in many organizations. The hand-held and head-mounted computers are tools to help collect information for improving the existing process, increasing awareness by construction workers of construction quality concerns, and promoting more scientific methods of improving construction operations.

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The contents of this paper reflect the view of the authors, who are responsible for the facts and the accuracy of the data presented herein.

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Automated Construction Field Data Management System

Bob G. McCullouch

A recently completed research project performed for the Indiana Department of Transportation (INDOT) to define and describe an automated construction field data management system is summarized. INDOT's field personnel typically spend 4 to 5 hr daily processing paperwork. The paperwork burden has reached a point where it distracts field personnel from performing their main task of supervising construction. This is typical of other state departments of transportation. The purpose of the project was to define a system that could be developed to ease this problem. In this project, current INDOT data management procedures and software systems were reviewed, a survey of other department of transportation field data management systems was performed, computer hardware and software tools were explored, system requirements were determined, and costs and benefits were calculated.

Department of transportation (DOT) construction supervision personnel spend a considerable amount of time processing construction data (construction data include material and test data), sometimes to the extent that it distracts them from their main task of directing and supervising the construction process. A recently completed research project for the Indiana Department of Transportation (INDOT) indicated that on a construction project the inspector and project engineer (PE) typically spend 4 to 5 hr daily processing paperwork (1). On the basis of existing trends of increased construction activity without parallel increases in INDOT personnel, data management will continue to expand, making more demands on time. Results of a survey performed under the INDOT research project indicate that the same scenario is occurring in other state DOTs. Not much can be done to reduce the amount of construction data generated and managed, but an innovative automated data management system could be developed to solve this problem.

DEVELOPMENT OBSTACLES

Typical obstacles that will probably be encountered during system development include lack of data integration within a DOT organization, hardware and software considerations, servicing the system user, overcoming the burden of DOT paper forms, and determining how to phase in automation.

A common problem among DOT organizations is the lack of integration between various data systems. For example, computer systems may exist within accounting, design, contracts, maintenance, materials and tests, and construction. Usually each operates as a stand-alone product with no link to the other systems. This has created "islands of automation" within a DOT organization. An effort needs to be made to link these data islands together to share information. Figure 1 shows these two data automation configurations.

To achieve integration between systems, an interface must exist. This interface is accomplished through hardware and software at the various user levels. Other factors affecting integration are the size of the DOT, its organizational structure (i.e., projects, districts, and central), personnel computer capabilities, user resistance, and organizational demands on the data.

To mitigate user resistance, the system should be designed around the users. Input should be solicited from the field, district, and central office personnel so that a user friendly system results.

Another obstacle is the process of going from paper to electronic forms. To expedite this, all pertinent forms should be studied. Each form should be reviewed to determine whether it will be needed and how it will be represented in the system. The study should also document the paths of forms so that electronic data trails can be designed.

User acceptance can be enhanced through staged implementation. Bringing the system on line on one project, several projects, or a district at a time will help to reduce start-up problems and user rejection.

CURRENT SYSTEMS

One activity of the INDOT research project was to survey other state DOTs to determine whether a system existed and to obtain a description of it. A survey was sent to 50 DOTs, and 44 were returned. Thirty-one DOTs indicated that a system was either operational or in some stage of development. Table 1 summarizes the responses of these states.

Software varied from a data base package such as dBase III+, to a higher, more powerful language, such as C. IBM PCs or compatibles were the machines used in the field, and those that transferred files electronically were equipped with modems. Hardware used at other levels varied from a PC to a mainframe. The mainframe and mini are used mainly for processing and data storage. In-house development costs averaged $100,000 to $400,000, and outside consultant costs went into the millions of dollars.

Currently (1991), the American Association of State Highway and Transportation Officials (AASHTO) is pursuing the development of a construction management system. This system will integrate with BAMS, another AASHTO software product, and provide some of the features identified in this

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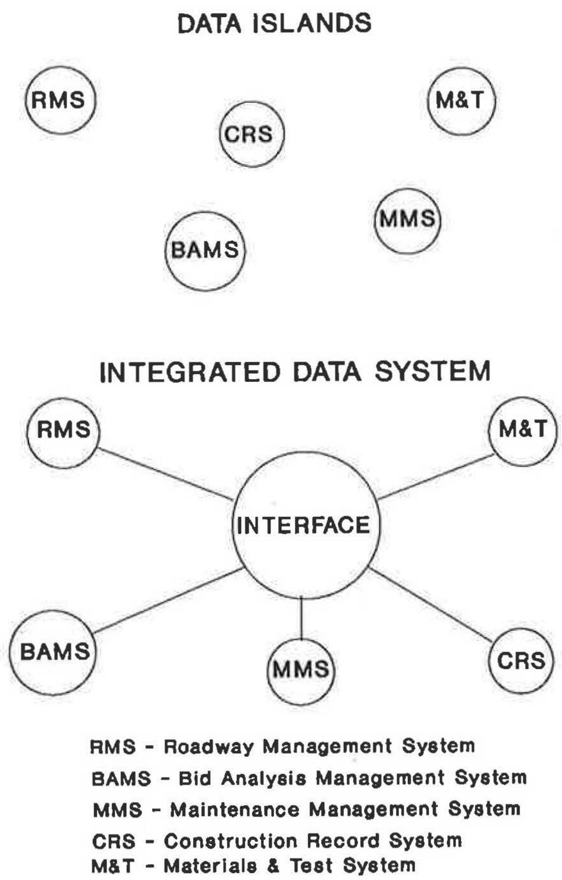

FIGURE 1 DOT data systems.

paper. The system will be mainframe based with PC tie-in from the field office. The purpose of the system is to computerize field operations by automating the paperwork process (*2*).

CONNECTICUT DOT SYSTEM

Perhaps the most mature system is found in Connecticut. In 1985 a $5 billion rehabilitation program began that burdened the existing construction data management system. To deal with this problem, CONDOT contracted with a consultant to design and develop a system. Development took 2 years, and the system went on line in summer 1988. Before the rehabilitation program started in 1985, approximately $80 million was spent each year on highway construction. CONDOT spent $750 million in 1990 for construction on approximately 250 projects. Approximately 400 CONDOT personnel are involved in supervising construction. Approximately 40 percent of the projects are managed by consultants, so in 1990 CONDOT will supervise approximately $450 million in construction with approximately 400 personnel.

To deal with this construction supervision problem, several management systems were identified and developed: the construction management and reporting (CMR) system, the preconstruction management system (PCMS), the executive reporting system (ERS), and the financial management information system (FMIS).

The CMR system is a PC stand-alone and interactive terminal system. Each project office is connected to the central office UNISYS mainframe via dedicated phone lines. Each workstation provides the user access to the CMR system as well as local data processing. Local computing capability includes spreadsheet, electronic memo or mail, and some engineering calculation capability. The Federal Highway Administration (FHWA) is tied into the system. Any field consultant can access the system as well. The system is ID and password protected.

The ERS is an information overview system used by upper management. Information used by the system is updated every night. This system is visually operated by using colors and the touch screen. Colors are used to indicate project condition on the basis of certain parameters (personal interview with A. Gruhn, CONDOT, 1990).

SYSTEM FEATURES

General system capability is the automation of construction field data. Initially this should encompass the capture, storage, and transfer of daily field-generated data, materials and test data, processing reports, and contractor payments.

Data integration should be a dominant system characteristic. Data collected and used in this system should be stored in a format that is accessible from other DOT computer systems. The hardware configuration should allow for the sharing of data between the various systems.

Hardware Configurations

On the basis of the previously mentioned premise of data integration, and because most DOTs use a mainframe and are organized by districts, three hardware options are considered feasible:

1. All storage and processing are handled on the mainframe. The PC acts as a terminal. Data accessibility is controlled at the mainframe by specifying user access codes. Communication costs are high because it is on line and interactive.
2. The mainframe is used as a storage device with processing required for managing the data base and communicating with users. Data reside at the mainframe, whereas the major processing is done at the PC level. PC acts in stand-alone and terminal environments. Stand-alone provides the user with additional computer capabilities. Processing the data at the PC lessens dependence on the mainframe. With batch transfer, communication costs can be greatly reduced. Batch transfer can be scheduled on a daily basis so that information is available the next day.
3. The mainframe is used as a storage device. At the district level a mini system will reside where data are received from the projects, stored temporarily, processed, and eventually stored on the mainframe. The PCs in the field do not communicate with the mainframe but go through the mini in the district. This lessens dependency on the mainframe so that users can operate in case it is down.

Option 3 was recommended to INDOT and is shown in Figure 2.

TABLE 1 State Responses to Survey

State	System Description
Alaska	Project Records Management Automated Weigh System
Arizona	Conceptually designed, awaiting funding.
Arkansas	Computerized Estimating system, PC based. Portable data collectors for inspectors.
California	Progress payment system, main frame based.
Colorado	Considering AASHTO's Construction Daily records program.
Connecticut	Operational system developed by consultant.
Illinois	Conceptual stage, PC based system.
Iowa	Conceptual stage.
Kansas	Developmental stage. Using consultant. PC at job site , data transfer to main frame.
Kentucky	Operational PC stand-alone system. DBase III+ compiled programs.
Maine	Some PCs in the field office with customized applications. Lab testing automation currently underway.
Maryland	Operational PC stand-alone system. DBase III+ compiled programs. Inspector's daily report data tracked.
Michigan	Operational stand-alone system. DBase III+ programs that processes project records, pay estimate,and tested materials.
Minnesota	Contract Administration Record System. Used to process pay requests. PC based.
Missouri	Operational system. DBase III+ programs that process the daily report.
New Hampshire	Developmental stage. PC based system, C language, fully automated system with tie-in to mainframe.
New Jersey	Automated Construction Estimate System(ACES). DBase III+ programs for producing monthly estimates.
North Carolina	Conceptual stage. PC system linked to main frame.
North Dakota	Operational system. PC stand-alone dBase III+ programs. Used for record keeping.
Ohio	Survey stage. Form study underway. Automate daily records and testing reports. Hired consultant.
Oregon	Continuing developing a system that will create an automated construction/maintenance system.
Pennsylvania	Operational documentation system. DBase III+ programs with electronic data transfer capability. Material and test system under development.
South Carolina	Developing construction system tie-in to BAMS.
South Dakota	Conceptual stage.
Texas	Interested in AASHTO's construction records program.
Vermont	PC field bookkeeping system. BASIC language.
Washington	Contract Administration payment system is operational. Construction Contract Information System operational - PC and main frame based. Developing materials and test program.
Wisconsin	Operational system. Daily work items tracked and monthly estimate produced. PC based with data transfer to main frame.

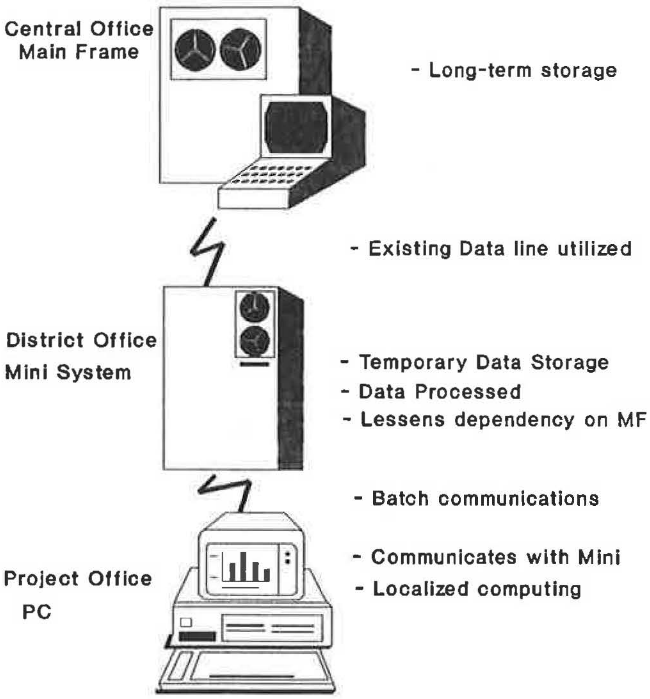

FIGURE 2 Hardware Option 3.

FHWA Guidelines

Since the system will be used on projects that fall under the jurisdiction of FHWA, certain established FHWA guidelines must be complied with (*3*). The guidelines are as follows:

- Provide for adequate backup and recovery of records to protect against information loss. Protection procedures should be in place to prevent both human and system failures.
- Prevent unauthorized alteration or erasure of electronic records.
- DOT must validate equipment reliability when records are created.
- Accurate audit trail must be present.
- Adequate data storage backup must be in place.

PC Computing

Computing capability should be available to the user at the PC level. Capabilities provided would give the user local computing capability and allow for user-developed personalized applications. At a minimum, the following software should be available: spreadsheet capability, data base manager, electronic mail, word processing, and volumetric calculation capability for earthwork and concrete calculations.

Miscellaneous Features

The features mentioned in this section are applications of some of the latest technologies in data management. These features act as accessories and could be a part of the initial system or phased in so that ultimately a paperless system could exist. A short description of each is provided.

Computerized Specs

Electronic specs means that the standard specs, supplemental specs, and special provisions will be stored and maintained in electronic form and made accessible to users. The user should have the ability to manipulate, process, and use the specs.

Portable Data Collectors

Using hand-held portable data collectors in the field brings automation to the data collection process. The portable device can be used to record testing, inspection, material delivery, or any information recorded remotely. The data can be batch uploaded into a PC for processing.

Asphalt/Concrete Plant Tie-In

Batch plant data such as batch numbers and weights can be recorded and transmitted electronically, eliminating most of the time and labor required in the manual process.

RF Tags To Record Quantity Installed

Radio frequency (RF) systems can be used to track and record hauled construction quantities. Tags that store hauled weight and number of trips are affixed to hauling units. This information is inscribed on the tag by passing the unit over a scale and RF scanner that writes it on the tag. The hauling unit essentially has a portable data base attached to it from which data can be retracted and uploaded into the data management system. This would eliminate the need for an inspector to count and measure quantities.

Bar Code Usage

Forms that have recurring fields of data could probably benefit from bar codes. Bar coded labels could be attached to testing samples and used to identify and track them through the testing process. Also, bar coded menu tablets could be used to quickly enter data into the computer. Use of bar codes can significantly improve data entry speed and at the same time reduce data entry error. The only equipment required would be a reader or scanner and software that can print the bar codes on the documents or labels.

Laboratory Equipment RS232 Interface

Laboratory and testing equipment can be equipped with RS232 ports so that data can be captured electronically into a computer system. This would eliminate manually recording the information and keying it into a computer.

Electronic Signature Control

Signature authorization is required to process many DOT forms, especially contractor progress payments. Technologies are available that provide this capability electronically. One is a plastic magnetic stripe card that is scanned when authorization is required. Another is touch screen technology, by which signatures can be recorded onto electronic documents.

Document Scanner

Use of document scanners is a way to quickly enter paper documents into electronic form. Certain forms and processes may lend themselves to this technology.

Electronic Clipboard Capability

With this device, field personnel can record information electronically much like they would with a clipboard and paper. Ideal applications are recording inspection information and drawing sketches electronically. This information can be uploaded into the data management system.

Initial Capabilities

All of these capabilities or features can be components of the system, but it may too complex and unnecessary initially. The system is conducive to staged development and implementation.

SYSTEM COSTS

System cost comprises software development, hardware, software, communication, system and hardware maintenance, data processing staff support, and training.

Software Development

Developing software could be the largest initial cost. Basically, three options exist, with some variations possible for each: consultant developed, in-house developed, and hybrid (in-house and consultant).

An outside consultant provides expertise and experience that potentially could produce a better product. Consultants usually have the manpower to devote to a project, so development time could be shorter. On the flip side, development costs will be higher.

Using in-house personnel to develop a system will be less expensive, but other factors must be considered. The availability and experience of data processing personnel to work on a project of this magnitude may be limited. This may cause a longer development time. But long-term maintenance support for the system may be better than a consultant because of internal system knowledge.

The third possibility is to have a mixture of in-house and outside consultant to supplement the development effort. The consultant provides additional expertise and experience, and DOT personnel can maintain more control over the final system makeup. This combination should also reduce costs.

After the system is operational, a system user depository should be established to incorporate user suggestions into future system revisions.

Hardware

Hardware components will be required at the various levels of the DOT organization. Equipment at the project site should include PC, monitor, printer, and modem. The modem is for transferring files between the field and district.

Hardware configuration Option 3 uses hardware at the district level for storing, processing, receiving, and sending data. Depending on district size and construction volume, the number of off-site users could range from 20 to 100. This hardware should not only support external users via phone lines, but also local network capability at the district office and communication with the mainframe. Most mini systems have this capability.

Software

Software will be needed at the PC for the system and localized computing capability, at the mini for data base management and communication, and at the mainframe for data storage. Software for local computing should include spreadsheet, data base management, electronic mail, word processing, and miscellaneous engineering calculation capabilities. Instead of buying software for each PC, it could be provided by the mini more economically. Other software needed at the mini is PC and mainframe communication and operating systems.

Communication

Transferring data from the field to the district or to the central office mainframe will have associated costs. The costs will depend on the frequency, duration, and distance of transmission. The options available are business telephone line with modem, dedicated data line, and the integrated digital services network. The business line and modem with batch processing is the most economical of the three options. A dedicated data line provides better data transmission but is much more expensive. A hypothetical economic comparison of these two options involving 300 INDOT projects indicated an annual cost differential of $1,500,000. The integrated digital services network is not as expensive as the dedicated line service, but in most states it is only available in limited areas.

Miscellaneous Costs

Costs from other sources will occur. Hardware and system maintenance, service, and update will be needed. A training program will be necessary to implement the system. This should consist of developing a training manual and conducting training sessions for system users. Securing project site hardware with extra locks, window bars, and other precautions will be another cost.

SYSTEM BENEFITS

The adoption of such a system will bring many benefits to a DOT. Most are hard to quantify but nevertheless will occur. The following are among the benefits: decisions will be based on complete information; the quality of information will be consistent; duplication of effort in recording and saving data will be eliminated; a better construction claims recording system will be provided; audit trails will be better defined, making it easier to track information; forecasting and trend analysis will be easier; accessibility of test results will be improved; credibility of data will increase; FHWA and consultant will have a tie-in; paperwork processing time will be reduced; supervision cost will be reduced; and the PE will be free of the paperwork burden.

Because valuable data will become easily accessible and retrievable, the following will be possible:

- More accurate future cost estimates,
- Tracking and processing of constructability data,
- Improved estimated quantities capability,
- Improved project duration estimates,
- Better tracking of roadway and structure status for construction and maintenance planning,
- Contractor performance records, and
- Ability to tie in to FHWA data base of information.

Savings will occur in postage, paperwork, form printing and storage, permanent record storage, management inquiries, and quality of the constructed project.

States that have developed and are using this type of system have documented some time benefits. In Connecticut, a pay estimate would take a PE 1 week at 75 percent time; now it is performed in 1 to 2 days. Stated earlier was that on an INDOT project about 5 hr per day is spent on paperwork. Of this time, 3.5 hr was spent by the PE. In comparison a PE in Connecticut spends 1 to 2 hr per day on paperwork. In New Jersey, by the manual method, it would take 1.5 hr to produce a daily report, 1.5 hr to produce a weekly report, and 4 hr to produce a monthly estimate. With the automated system these same reports are produced in 10 min, 15 min, and 20 min, respectively. Missouri DOT says its system is saving $0.5 million a year with improved accuracy.

CONCLUSIONS

Development and implementation of the system will require a considerable amount of effort, coordination, and cooperation. But before this system can become reality, it has to be perceived by management as necessary and a priority. Two realities should not be overlooked. One is that with transportation facilities continuing to deteriorate and heavier use expected, more construction will be needed to keep pace with demand. Second, because of a shrinking work force, fewer DOT personnel will be available to manage construction projects. These realities should demand the development and use of an automated construction data management system.

ACKNOWLEDGMENT

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Analysis and Evaluation of a Plan Quality Evaluation Form

JEFFREY S. RUSSELL AND GORDON D. SEVERSON

The results of an investigation to analyze and evaluate a plan quality evaluation form that was developed by the Wisconsin Department of Transportation (WisDOT) are presented. Forty projects were selected by WisDOT to be used in testing the effectiveness of the evaluation form. Second, a questionnaire survey of the state departments of transportation (DOTs) in all 50 states, the District of Columbia, and Puerto Rico was conducted. The survey provided information about procedures used in other states to evaluate the quality of highway plans. A large number of state DOTs have procedures for evaluating the quality of project plans and specifications. Third, interviews were conducted with the prime contractors and designers of the 40 projects that were selected for the test of the form. The results obtained from the prime contractor interviews were similar to the comments received from the test of the evaluation form. Finally, alternatives to accomplish plan quality evaluation were developed and analyzed for possible effectiveness. The alternatives that were developed were to (*a*) do nothing, (*b*) use narrative project critiques, or (*c*) use an evaluation form. The researchers recommended that WisDOT develop a new evaluation form based on the forms used by other state DOTs. This form could be used in a postconstruction meeting between representatives of the designer, prime contractor, FHWA, and WisDOT, if found necessary. The researchers further recommended that an evaluation not be performed for every project and presented guidelines that can be used to determine the selection of a project for evaluation.

In the past, nearly all highway designs were performed inhouse by state designers. In recent years, many state departments of transportation (DOTs) have lost qualified engineers to retirement. Many of these state DOTs have not been able to replace these engineers because of budgetary cuts and a lack of available civil engineering graduates entering the highway construction field. As a result, there is a lack of adequate resources at the state level. In addition, there has been a movement in recent years to privatize many of the services previously or currently performed by government agencies. For these reasons, there has been an increased use of design engineer consultants in the preparation of highway designs.

Many design engineer consultants are inexperienced in the preparation of highway project plans and specifications. These consultants, however, are gaining experience in the area by obtaining and completing design contracts with state DOTs. It is believed that the trend of hiring design engineer consultants to perform necessary functions for state DOTs will continue.

Poor-quality plans and specifications can affect contractor efficiency, increase the likelihood of contractor failure, and increase the amount of resources required of the constructor, designer, and owner in preparing change orders, negotiations, mediation, and litigation. Research has found that the probability of contractor failure is higher on projects that have a large number of design errors and omissions (*1*). Hence, high-quality design documents facilitate efficient construction through reduced costs, fewer changes, reduced number of disputes, better schedule performance, and higher quality in the final constructed facility. Consequently, a method to measure the quality of plans produced by both state design engineers and design engineer consultants needs to be developed.

The approach and results of a 10-month research investigation conducted for the Wisconsin Department of Transportation (WisDOT) are described (*2*). The purpose of the investigation was to analyze and evaluate a plan quality evaluation form that was previously developed by WisDOT. Alternatives for accomplishing plan quality evaluation are also presented along with the final recommendation that was made to WisDOT.

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RESEARCH APPROACH

The objectives of this research investigation were (*a*) the identification of the individual entities associated with the highway design and construction processes; (*b*) the development of suggested modifications to the existing evaluation form, (*c*) the development of alternatives to the evaluation form, and (*d*) recommendation of a future course of action regarding constructibility analysis and review for WisDOT.

The scope of the investigation was limited to the analysis and evaluation of a WisDOT-developed evaluation form. Selected prime contractors and design engineer consultants involved in grading, asphaltic cement concrete (AC) paving, portland cement concrete (PC) paving, and bridge projects were contacted. In addition, design engineers within the WisDOT districts were contacted. As part of the investigation, a questionnaire survey of the state DOTs in all 50 states, the District of Columbia, and Puerto Rico was conducted.

WisDOT-Developed Evaluation Form

Personnel in WisDOT Central Office recognized the importance of quality design documents in the success of a project and developed a postconstruction plan quality evaluation form during fall 1990. The form was sent to the prime contractors of 40 selected projects. The form asked the prime contractor to evaluate five specific areas of the project's plans. The form contained a description of the basis that was to be used during the evaluation of the contract provisions and construction plan. The form asked for a numerical rating of each of the specific areas. The possible numerical ratings were whole numbers between 0 and 10. A 0 rating indicated that the area was totally inadequate and unacceptable. A rating of 10 indicated perfection. A rating of 5 (acceptable) was defined as plans and specifications that substantially met the stated basis for evaluation. The numerical ratings would then be averaged for a composite rating for the project. Space was provided for written comments about each of the specific areas. A copy of the developed plan quality evaluation form can be found in Russell and Severson (*2*).

Projects Selected for Evaluation

The previously described evaluation form was sent to the prime contractors of 40 selected projects. The 40 selected projects included 10 grading, 10 AC paving, 10 PC paving, and 10 bridge projects. Table 1 indicates that the minimum, average, and maximum contract amounts for the 40 projects were $119,000, $2,244,667, and $11,256,000, respectively. The 40 selected projects included 26 prime contractor organizations and 21 design organizations. Of the 21 design organizations, 8 were WisDOT districts, 1 was a city designer, and 12 were design engineer consultants. A total of 18 design engineer consultant–prepared designs and 22 state-prepared designs were selected for evaluation.

Results from Evaluation Forms

Of the 40 evaluation forms sent out, 28, or approximately 70 percent, were returned. The group of returned forms represented 20 different prime contractor organizations. The largest number of responses came from the grading (8) and bridge (8) prime contractors. The fewest responses came from the PC paving prime contractors (5). Seven responses were received from the AC paving prime contractors. The group of returned forms represented 16 state-prepared projects and 12 design engineer consultant–prepared projects.

Table 2 indicates that the average overall project rating by project type varied from 4.1 to 5.6. The average overall rating for all projects was 4.9. This average rating indicates that the project plans and specifications were prepared to an acceptable standard. Table 2 also indicates that state-prepared projects received higher average ratings than design engineer consultant–prepared projects for every project type except PC paving projects. There are two possible reasons why the state-prepared projects received higher ratings: (*a*) because of the state's experience in preparing highway projects, the state-prepared projects are of an overall higher quality than design engineer consultant–prepared projects; and (*b*) the prime contractors completing the evaluation forms gave higher ratings to the state-prepared projects because of a fear that a low rating would adversely affect the relationship between the prime contractor and WisDOT.

TABLE 1 Contract Amount and Type of Projects Selected for Evaluation

Project Type	Sizes of Projects Selected for Evaluation		
	Minimum	Average	Maximum
Grading	$982,000	$2,975,900	$5,887,000
A.C. Paving	$593,000	$1,757,100	$2,443,000
P.C. Paving	$563,000	$3,277,200	$11,256,000
Bridge	$119,000	$799,200	$2,050,000
Overall Sample	$119,000	$2,244,667	$11,256,000

Written Comments from Evaluation Forms

The written comments from the evaluation forms covered the following six general areas: right-of-way difficulties, utility location difficulties, sequencing difficulties, inadequate field and soils investigations, equipment capabilities and limitations not considered, and constructibility difficulties.

Questionnaire Survey of State DOTs

A questionnaire survey was developed and sent to the DOTs in all 50 states, the District of Columbia, and Puerto Rico. Responses were received from 39 states and the District of Columbia. This is a response rate of approximately 77 percent. The objectives of the questionnaire survey were to (*a*) determine the amount of design work prepared by outside design consultants in other states, (*b*) identify previously established procedures for evaluating contract specifications and con-

TABLE 2 Summary of Ratings from Evaluation Forms by Project Type

	Project Type				Average Ratings
	Grading	A.C. Paving	P.C. Paving	Bridge	
State Prepared Designs					
Minimum Rating	4.0	4.0	4.0	5.0	4.3
Average Rating	4.8	5.8	4.7	5.0	5.1
Maximum Rating	5.0	8.0	5.0	5.0	5.8
Consultant Prepared Designs					
Minimum Rating	2.0	4.0	5.0	4.0	3.8
Average Rating	3.5	4.0	5.5	4.6	4.4
Maximum Rating	5.0	4.0	6.0	5.0	5.0
Overall Ratings					
Minimum Rating	2.0	4.0	4.0	4.0	3.5
Average Rating	4.1	5.6	5.0	4.8	4.9
Maximum Rating	5.0	8.0	6.0	5.0	6.0

struction plans, and (*c*) obtain the results of any previous investigations regarding the evaluation of the quality of contract specifications and construction plans. The questions in the survey were used to compare methods of evaluating contract specifications and construction plan quality used by different states. Questions were asked to determine who is involved in the evaluation, what types of projects are evaluated, what specific areas are evaluated, and what criteria are used to evaluate these areas.

The questionnaire first asked the states what percentage of projects designed in their state were designed by design engineer consultants. The responses varied from 0 percent (North Dakota) to 85 percent (New Jersey). The average percentage of designs performed by design engineer consultants was 26 percent.

The questionnaire next asked whether the states had procedures for evaluating construction project contract specifications. Sixty percent (22/37) of the respondents to this question had procedures for evaluating construction contract specifications. The questionnaire also asked whether they had procedures for evaluating the quality of construction plans. Seventy-four percent (29/39) of the respondents to this question did have procedures for evaluating the quality of construction plans. Clearly, a large number of state DOTs are evaluating the quality of project plans and specifications.

The states were then asked who was involved with the evaluation of construction plans. Table 3 indicates that approximately 90 percent of all states responding to this question solicit comments from state personnel involved in the project. Twenty-one percent of the states answering this question formally solicit comments from the prime contractor. Several other states indicated that even though they do not formally solicit comments from the prime contractor, they do informally solicit their comments.

The states were next asked whether evaluations were performed for every completed project. Seventy-one percent (20/28) indicated that they perform evaluations for every completed project. The balance of the sample, 29 percent (8/29), are states that do not evaluate every project. These states were then asked what percentage of completed projects are evaluated. As Table 4 indicates the percentage of completed projects evaluated varied from 7 (Maryland and Oklahoma) to 50 (Virginia). The average percentage of projects evaluated, where the state did not evaluate every project, was approximately 20 percent of completed projects.

States that did not evaluate every project were also asked what types of projects are evaluated. Thirty-eight percent (3/8) of the respondents to this question evaluate a sample of projects of every type and size. Twenty-five percent (2/8) of the respondents to this question evaluate only projects designed by design engineer consultants.

The states were next asked what specific areas of the construction plans were evaluated. Table 5 shows that nearly 90 percent of the states responding evaluate the sheets showing the estimate of quantities and the sheets showing the plan, profile, and cross-section details. The specific areas least evaluated are the standard and supplemental specifications, special provisions, and addenda. Even though these areas were the least evaluated, nearly 80 percent of the states responding evaluate them.

The states were finally asked what criteria are used to evaluate the specific areas. Table 6 shows that 93 percent of the states responding use sound engineering thought, judgment, and practice as one of the criteria. The next criteria used are whether the plan was clear, easy to understand, and bid and whether the plan contained information that was correct, complete, and adequate for the purpose. The criterion used least often was whether the design incorporated innovative and original ideas.

TABLE 3 Participants Involved in Project Evaluations

Participant	Number of Responses (N=29)	Percent
State Personnel	26	89.7
Design Engineer Consultant	8	27.6
Prime Contractor	6	20.7
Subcontractor	3	10.3

TABLE 4 Percentage of Completed Projects Sampled

State	Percent
Virginia	50
North Carolina	25
Hawaii	20
Arkansas	15
Nevada	10
Maryland	7
Oklahoma	7
Illinois	Random

TABLE 5 Specific Areas Evaluated

Specific Area Evaluated	Number of Responses (N=28)	Percent
Estimate of quantities sheets, miscellaneous estimate sheets, and computer earthwork sheets.	25	89.3
Plan and profile sheets, structure detail sheets, and cross section sheets.	25	89.3
Title sheet, typical sections, general notes, index of drawings, miscellaneous detail sheets, alignment diagrams, and standard detail sheets.	24	85.7
Traffic control plan, erosion control plan, and other special plans.	24	85.7
Standard specifications, supplemental specifications, special provisions, and addenda.	22	78.6

TABLE 6 Criteria Used as Basis for Evaluation

Criteria Used as Basis for Evaluation	Number of Responses (N=28)	Percent
Design demonstrated sound engineering thought/judgment/practices.	26	92.9
Plan was clear, easy to understand, and to bid.	25	89.3
Information was correct, complete, and adequate for the purpose.	25	89.3
Sequencing and staging of activities were included.	23	82.1
Soils investigation recommendations were included.	22	78.6
Utility and railroad needs and conflicts were included.	22	78.6
Outside influences and sources of conflict were considered.	20	71.4
Design was cost effective.	20	71.4
Plan was well-organized, well-formatted, and professionally drafted.	20	71.4
Plan was clean, uncluttered, and free of unneeded detail.	18	64.3
Capabilities of construction personnel and equipment were considered.	15	53.6
Design incorporated innovative and original ideas.	10	35.7

Prime Contractor Organization Interviews

The prime contractors that were selected to be interviewed were those who constructed the 40 projects that were selected by WisDOT for evaluation. In most cases, it was possible to meet with the person who completed the plan quality evaluation form that was sent to the prime contractor. As stated earlier, the 40 selected projects were constructed by 26 different prime contractor organizations. Of this group, 20 prime contractors were able to be contacted for interviews. The other six were not interviewed after numerous attempts to contact them failed. Fifteen of the interviews were conducted in person, and the remaining five were conducted by telephone.

During the interviews, the prime contractor representatives were asked a set of approximately seven questions. These questions had three objectives: to identify the types of difficulties the prime contractor has encountered in past project designs, to identify how the prime contractor would like to communicate feedback to the project designer, and to identify how often this information should be communicated.

From the interviews conducted, several areas where prime contractors have had difficulties with project designs were identified. Five of these areas were consideration of equipment capabilities and limitations, lack of adequate field and soils investigation, inaccurate quantity estimates, utility coordination difficulties, and soil quantities for staged projects not listed by stages.

The prime contractors were also asked how feedback about a project should be communicated to the project designer. Half (10) of the prime contractors were supportive of an in-person meeting near the completion of the project. The meeting could include representatives of the designer, prime contractor, subcontractors, FHWA, and WisDOT. These prime contractors believed that in-person meetings would be more effective in communicating their difficulties with the project design than written comments.

Four prime contractors were not supportive of in-person meetings because they believed that the meetings would require too much time and would be difficult to schedule. Another reason of nonsupport was a fear that the meeting would turn into an argument rather than a constructive meeting for the exchange of ideas and comments.

Six prime contractors were supportive of an evaluation form similar to that already developed. Those prime contractors favoring an evaluation form believed that the form could be successful if results from the form were incorporated into future projects. One representative of a prime contractor organization stated that he would support an evaluation form if the amount of time required to evaluate the project equaled the amount of time spent by WisDOT evaluating the prime contractors. Three of the prime contractors not supportive of an evaluation form were not supportive because the form would add to the paperwork that they currently have to complete for WisDOT projects.

Several other suggestions of how to communicate feedback to designers were received: have the designer present at or involved in the final inspection of the project, have the contractor communicate project feedback to the project engineer who would in turn communicate the information to the designer, and maintain and possibly expand the current annual designer-contractor meetings held through the Wisconsin Road Builders Association to include a discussion of difficulties encountered by contractors on specific project details.

The prime contractors were finally asked how often they would like to provide feedback to the project designer. Half (10) of the prime contractors stated that they would like to provide feedback for every project. If providing feedback for every project were not possible, several suggestions were offered: randomly sample all project types and sizes; evaluate only projects where major difficulties were encountered; have the prime contractor choose the project to comment about; base the selection of projects on type, size, and complexity; and select projects with unique or unusual conditions.

Designer Organization Interview

The designers selected to be interviewed were those who designed the 40 projects selected by WisDOT for evaluation. Many times it was not possible to meet with the actual designer of the project because multiple individuals were involved in the design. However, meetings were scheduled with representatives of the design organizations that were familiar with the projects and served as managers or supervisors of highway design. As stated earlier, the 40 selected projects were designed by 13 design engineer consultants and 8 WisDOT design sections. Seventeen of these design organizations were contacted for interviews (11 design engineer consultants and 6 state design sections). One additional WisDOT design section not included in the projects selected was also contacted. Eleven of the interviews were conducted in person, and the remaining seven interviews were conducted by telephone.

During the interviews, the representatives of the design organization were asked a set of approximately five questions. The questions were meant to determine whether feedback about projects from contractors would be helpful to designers, what type of information from contractors would be helpful, in what form the information would be most helpful, and how often this information should be communicated to the designers.

From the interviews conducted, it was determined that constructive feedback about completed projects from highway construction contractors would be helpful. The designers were next asked what types of information from contractors would be helpful. Examples of the types of information that designers were interested in receiving from contractors included equipment capabilities and limitations, accuracy of estimate of quantities, adequacy of traffic control plans, adequacy of soils investigation, cost-effectiveness of the design, completeness of plans, clearness of plans, and ease of understanding of plans.

The designers were next asked in what form the information from contractors would be most helpful. Several ways of communicating feedback were suggested. One suggestion involved having the prime contractor use an unmarked set of plans during construction. When difficulties were encountered during construction, the contractor could mark the difficulties on the set of plans. After construction, a follow-up meeting between the prime contractor, designer, FHWA, and WisDOT representatives to discuss the difficulties encountered could be scheduled. Related to this was a suggestion to have the prime contractor submit written comments and, if necessary, conduct a follow-up meeting between representatives of the prime contractor, designer, FHWA, and WisDOT.

Other suggestions were related to conducting meetings either during the project at a major milestone or at completion of the project. The meetings could be between the representatives of the prime contractor, designer, FHWA, and WisDOT. The remaining suggestions included having the designer visit the project during the construction or having the designer involved with the final inspection of the project.

The designers were next asked how often they would like to receive feedback information from the contractors. Most designers responded that they would like to have feedback from every project. Since this may not be possible, the designers were also asked how projects should be selected for evaluation. The following criteria were suggested: random sampling of all project types and sizes, major projects only, only projects that encountered major difficulties, projects that were unique or had unusual conditions, projects that had difficulties that might be of interest to designers, and projects selected by the project engineer.

The designers were finally asked for general comments regarding feedback from highway contractors. Nearly all of the designers stated that specific written comments, both positive and negative, from the contractors would be more helpful than a numerical rating number that indicated the quality of the plans. Most designers also stated that a meeting between the designer, prime contractor, FHWA, and WisDOT representatives could also be helpful in communicating difficulties encountered during a project. With regard to the meetings, some of the design engineer consultants were concerned that their firms would not be compensated for the time required for a representative of their firm to attend these meetings. Thus, a method to compensate the design engineer consultants for their time would have to be developed. Other designers commented on the existing plan quality evaluation form, stating that if a rating number continued to be used, the range of possible ratings should be narrower and more meaning should be attached to the individual rating numbers. Other designers suggested that the Wisconsin Road Builders Asssociation be further used to help enhance communication between prime contractors and designers.

During the interviews with the representatives from the WisDOT design sections, several methods and forms for project evaluation were identified. Most districts have the state project engineer complete an evaluation form at the end of the project. Other districts had the state project engineer write a narrative project critique at the completion of a project. The narrative described the difficulties encountered with the plans and areas of the plan that worked well in the field. These project critiques are circulated through the district's inhouse design and construction staffs as well as any consultants involved.

ALTERNATIVES TO ACCOMPLISH PLAN QUALITY EVALUATION

From the results of this investigation, three possible alternatives to accomplish plan quality evaluation were identified: do nothing, narrative project critique, and evaluation form. Within the evaluation form alternative, four options are available for the development of such a form: use the existing WisDOT plan quality evaluation form, modify the existing WisDOT plan quality evaluation form, adopt a form developed by another state DOT, and modify a form developed by another state DOT to meet the specific needs of WisDOT.

To analyze the possible effectiveness of each alternative, it was necessary to develop a framework to be used. To be effective, each alternative should answer five questions. As Table 7 indicates, the five questions are what, why, who, when, and how. Specific answers to these questions with the exception of "when" and "how" are also presented in Table 7. To answer the "what" and "why" questions, each alternative should evaluate plan quality because plan quality can affect the performance achieved on a project. To answer the "who" question, each alternative should involve a representative from at least one of the following project participants: prime contractor, designer, FHWA, and WisDOT.

The question of when the evaluation should be performed has two parts: (*a*) the selection of the project to be evaluated and (*b*) once selected, the timing of the evaluation during the construction of the project. Several options are available to determine when a project should be selected for evaluation: evaluate every completed project, evaluate a fixed percentage of each type of project completed, evaluate only design en-

TABLE 7 Implementation Considerations Related to Alternatives

Question	Response
What?	Evaluate plan quality.
Why?	Plan quality impacts cost, schedule, quality, and safety achieved on project.
Who?	Participants involved in the project (i.e., prime contractor, designer, FHWA, and WisDOT).
When?	Selection of project and timing of evaluation during construction of project.
How?	Means by which WisDOT performs plan quality evaluation.

gineer consultant–prepared projects, evaluate projects that encountered difficulties, and evaluate projects with unique or unusual characteristics or conditions.

The second part of the "when" question is that once a project is selected for evaluation, when during the construction of the project should the evaluation take place. Several options are available: evaluation at 33 percent, 66 percent, and completion of the project; evaluation at 50 percent and completion of the project; and evaluation at completion of project only.

The following sections describe "how" each plan quality evaluation may be performed.

Do Nothing Alternative

This is the least effective method to accomplish plan quality evaluation. This alternative fails to answer any of the five questions that were presented as part of the framework to analyze the alternatives. As a result, the do nothing alternative is not a feasible alternative to accomplish plan quality evaluation and is discarded as a practical alternative.

Narrative Project Critique

This alternative consists of having the state project engineer write a narrative project critique at the completion of the selected project. The critique should include a description of items that caused difficulties during construction as well as descriptions of items that worked well during construction. An advantage of this alternative is that it could provide design engineers with specific comments from the perspective of the state project engineer on difficulties encountered rather than generalities. This alternative would be an efficient means of evaluating a project when no significant difficulties were encountered.

A disadvantage of this alternative is that comments from the prime contractor may not be directly incorporated into the project critique. Another disadvantage is that the critique could become lengthy and, as a result, may not be read by designers. Also, this format is open ended and ill structured. Hence, there is not a standard format to present the comments. This would complicate the compilation and analysis of the data. Another disadvantage is that the meaningfulness of the results could be suspect because of the variability between individuals writing the critique. A final disadvantage is that this alternative does not provide a relative assessment of design engineer consultant performance.

Evaluation Form Alternative

This alternative consists of using a form to guide the evaluation of plan quality. The form could be filled out directly by the prime contractor or the state project engineer. It could also be used as a guide for discussion between the designer, prime contractor, FHWA, and WisDOT representatives at an end-of-project meeting. An advantage of using a form for evaluation is that it could allow for direct comments from the prime contractor. Also, if used at an end-of-project meeting as a guide for discussion, communication between the designer, prime contractor, FHWA, and WisDOT representatives could perhaps be enhanced. A disadvantage of using a form for evaluation is that the prime contractor may not fill out the form. Another disadvantage is that an end-of-project meeting between the designer, prime contractor, FHWA, and WisDOT representatives may be difficult to coordinate and schedule. Also, the prime contractor and designer representatives may not be willing to spend the time to attend such a meeting.

As mentioned previously, the following four options are available for the development of a plan quality evaluation form:

1. Use existing plan quality evaluation form. This option would require the least effort on the part of WisDOT. However, on the basis of the test conducted using the existing evaluation form, the meaningfulness and usefulness of the results obtained are suspect.
2. Modify existing plan quality evaluation form. This option consists of several possible modifcations that could be made to the existing evaluation form: (*a*) shorten the range of possible rating numbers and explicitly define the meaning of each number; (*b*) convert the form from a combination of rating numbers and written comments to one of written comments only; (*c*) reformat the form to one with specific questions to meet the needs of WisDOT; (*d*) reformat the form into a checklist where different areas to be evaluated are listed with the possible responses; and (*e*) integrate modifications (*b*),

(*c*), and (*d*) into a form with a checklist for easily answered questions, specific short answer questions to meet the needs of WisDOT, and a section for written comments. Each of these modifications would make the form easier to use and would help ensure that the information obtained from the form would be meaningful and useful to the designer of the selected project and future projects.

3. Adopt a form developed by another state DOT. From the questionnaire survey of the state DOTs, several copies of forms used by other states were obtained. The formats of these forms ranged from specific questions about the project to checklists of easily answered questions.

4. Modify a form developed by another state DOT. The form could be modified to incorporate positive attributes of several different forms used by other state DOTs and further modified to meet the specific needs of WisDOT.

RECOMMENDATIONS

On the basis of the research and findings described in this paper, the researchers recommended the development of a new form based on the forms from other state DOTs. This will enable WisDOT to take advantage of the positive attributes of each form. Figure 1 shows a sample form that was developed for consideration by WisDOT. This form was reviewed by WisDOT staff and modified to better meet the needs of WisDOT. The form is currently being implemented by WisDOT.

This form consists of three parts. The first part consists of a checklist that rates items of the plan that appears to be straightforward. The possible responses to the items would be either qualitative in nature (e.g., excellent, good, fair, or poor) or simply yes or no. The number of possible qualitative

PART I -- Checklist

Were the plans complete?
_____ Very complete _____ Generally complete _____ Several omissions _____ Many omissions

Could you easily stake the project from the plans?
_____ No problems _____ Few problems _____Some problems _____ Serious problems

Were the quantities correct?
_____ Correct _____ Some errors _____ Several errors _____ Large errors

Was the drafting of – _____ Excellent _____ Good _____ Fair or _____ Poor quality?

Was the plan accuracy – _____ Excellent _____ Good _____ Fair or _____ Poor?

Did the plans contain – _____ Few _____ Several _____ Many or _____ Serious errors?

Were the plans – _____ Very easy _____ Easy _____ Difficult _____ Very difficult to read?

If the Designer or Consultant was called on to make changes, was the response –
_____ Effective _____ Slow _____ Poor or _____ Ineffective?

Would you rate this Designer or Consultant's plans –
_____ Better _____ About the same or _____ Inferior to other Consultant designed plans?

Would you rate this Designer or Consultant's plans –
_____ Better _____ About the same or _____ Inferior to other Department of Transportation designed plans?

If the Designer or Consultant produced similar plans, would you recommend that the Designer or Consultant be –
_____ Used again _____ Given work ahead of other consultants
_____ Never given more work or _____ Given a penalty?

FIGURE 1 Sample evaluation form for consideration. ***(continued on next page)***

PART II -- Short Answer Questions

Roadway

Were the quantity summaries correct? State any major departure from plans quantity and reason for same.

Were there any problems in location in the field? If so, state problems.

Was right of way detailed properly?

State any other facts that may have presented problems relative to plans.

Were incidental items (i.e., embankment curbs, down drains, catch basins, etc.) properly located?

Earthwork

Was soil profile reasonably accurate as to type of material encountered?

Structures

Were dimensions, details, and elevations accurate?

Were any Change Orders required? Explain the purpose and the need.

In your opinion, what could have been done to improve the structure plans?

Traffic and Signing

Were the traffic and signing plans complete and accurate?

Was the detour striping plan clear and accurate?

Were there any problems associated with the temporary concrete barriers?

Were there any problems encountered with installing delineators? Were the delineator quantities reasonably correct?

Special Provisions: Bidding Schedule

Although the special provisions supersede the plans, were there any apparent contradictions between them?

Were there any items normally specifically paid for but left out of the bidding schedule?

Were there any ambiguities within the special provisions?

What might have been done to improve the special provision?

Were any change orders necessary that resulted from errors, omissions, or ambiguities in the plans, special provisions, and bidding schedule? Explain briefly.

PART III -- Additional Comments

This section is for written comments related to difficulties encountered that require further elaboration.

FIGURE 1 ***(continued)***

responses should be few in number. By having fewer choices for responses, more meaning will be attached to each of the possible responses. There should also be a section in the first part where comments regarding adverse conditions related to the items in the checklist could be recorded. This section of the form could easily be filled out and should not require much time of the evaluator. Second, by scanning the responses, a designer could get a general impression of the quality of the plans without reading several pages of text.

The second section of the form consists of several short-answer questions. The questions posed in this section should address areas where WisDOT has perceived the most difficulties or provide designers with beneficial information that could be used when preparing designs for future projects. The questions should be posed in such a way that the evaluator is encouraged to write more than short and simple responses.

The third section would allow additional comments regarding the project to be noted. This section would be of benefit to the evaluator because it would allow for further descriptions of specific difficulties that were encountered and suggestions for improvement. This section would also be of benefit to designers because the specific comments and suggestions could help the designer in the preparation of future designs.

The selection of projects for evaluation should be based on the professional judgment of the WisDOT project engineer and construction area supervisor. Criteria that could be used to select projects are whether there were many questions regarding the intent of the design during bidding and construction, whether there were a large number of change orders due to design errors and omissions, or whether the project contained any unique or unusual conditions or characteristics. The researchers did not recommend the evaluation of every project, nor did they recommend evaluating a fixed percentage of projects. The reasoning is that there is no reasonable justification for consuming the scarce time resources of the prime contractor, designer, FHWA, and WisDOT representatives when the quality of the plans was fine and no significant difficulties were encountered. As a result, this scheme of implementation will evaluate project quality by exception. Not selecting a project for evaluation implies that the plan quality was fine and no significant difficulties were encountered. Success of this implementation scheme depends on the appropriate use of judgment by the project engineer and construction area supervisor.

The use of the evaluation form at the project level should involve the prime contractor, designer, FHWA, and WisDOT representatives. The researchers recommended that if a project is selected for evaluation, a postconstruction meeting between the prime contractor, designer, FHWA, and WisDOT representatives be conducted, if necessary. The evaluation form could be used as a guide for discussion during the meeting.

Following the evaluation of a project, the comments and suggestions received should be passed to the district construction supervisor, who would in turn submit the evaluations for that district to a designated person within WisDOT Central Office. The results from the meetings and evaluation forms should be compiled jointly by the Central Office Design and Construction sections into a report. A possible outline for this report could be (*a*) Introduction, (*b*) Summary of Difficulties Encountered, (*c*) Suggestions for Improvement, and (*d*) Conclusions. The report could then be disseminated to state designers as well as design engineer consultants. It could also be used as part of an expanded designer-contractor annual meeting held by the Wisconsin Road Builders Association. The meeting would communicate the difficulties encountered in project designs and the suggestions for improvement.

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Cost Overruns on State of Washington Construction Contracts

JIMMIE HINZE, GREGORY SELSTEAD, AND JOE P. MAHONEY

The completion of construction projects within budget is of paramount importance to most owners. Yet, it is common knowledge that numerous factors can cause the costs of construction to exceed the budget. Understanding the specific causes of cost overruns can serve as the beginning stage for controlling costs. Research was conducted to evaluate construction cost overruns on projects completed for the Washington State Department of Transportation. The objective was to identify factors that have the strongest association with construction cost overruns. Results of the analysis, which examined information from 468 construction projects, indicated that cost overruns, expressed as a percentage of the original contract amount, tend to increase with the size of the project. Evidence also suggests that the cost overrun rate increases with the number of bidders and with the increased dispersion of the various bids submitted per project.

In the early stages of the design of a project, the primary objective is to establish the parameters that must be met to meet the goals of the owner. Whereas the functional aspects of the owner's needs in a project receive paramount attention, the financial constraints imposed by the owner will weigh heavily in many design decisions. When the design is complete, the project is advertised and the construction documents are distributed to firms that will submit bids on the project. The construction contract is typically awarded to the lowest qualified bidder submitting a regular bid. Under ideal circumstances, the final or ultimate cost of the project to the owner will be the same as the amount stated in the construction contract. However, in reality, the final costs incurred on construction projects are rarely the same as stated in the contract.

On unit-price contracts, it is generally accepted that the final cost of a project will differ from the amount on which the low bidder was determined. This is because the number of units to be installed, excavated, placed, or removed cannot be determined with complete accuracy. If such accuracy were attainable, the projects would be awarded on the basis of fixed-price contracts. Other reasons for cost differences between the contracted amount and the final cost of construction include omissions of crucial information in construction documents, errors in construction documents, the discovery of changed conditions or differing site conditions, changes in the project that are authorized by the owner, interference in construction operations by personnel of the owner, and a variety of other reasons that will result in an increase in cost to the owner. Whatever the source of the change in construction costs, the increase is typically referred to as an overrun. The "overrun rate" is the change in the construction cost of a project, stated as a percentage, compared with the original contracted amount.

Are construction cost overruns random? Can cost overruns be predicted or modeled? If so, efforts can be better directed to decrease or at least control the overrun rates. Can some increased understanding of cost overruns be achieved? If so, budgetary decisions will be more enlightened and accurate. In response to these questions, a study was conducted through the Washington State Transportation Center at the University of Washington to provide insights into cost overruns on Washington State Department of Transportation (WSDOT) construction projects.

LITERATURE REVIEW

Several research efforts have been made to identify variables that are most closely associated with cost overruns. Despite the large number of researchers that have considered this topic, little consistency exists between the findings of various researchers.

Several studies have indicated that the cost overrun rate is influenced by the type or size of project. One study indicated that cost overruns were disproportionately larger when the project size was increased (*1*). Larger projects, associated with greater complexity, are subject to a greater number of change orders, which may be the cause of significant cost overruns (*2*). However, another study found that the change order rate was reduced on larger projects (*3*). One study indicated that cost overruns were less predictable on small projects, but that larger projects consistently encountered some but rarely excessively large overruns (*4*). Another researcher found that the type of project influenced the overrun rate (earthwork and paving projects had higher overrun rates) (*5*).

Other studies have indicated that the cost overrun rate is not necessarily related to the project itself but to the nature of the competition on the project. One measure of the competitive nature of the bidders is to compare the low bid with the owner's estimate or the engineer's estimate. Whereas it may be concluded that poor economic conditions will cause bids to be below the engineer's estimate (*6*), it has also been stated that the estimates generated by the owner are conservative in most cases (*7*). One study indicated that cost overruns were largest when the low bid was below the owner's estimate. The interpretation offered was that contractors may regard the difference between the low bid and the engineer's estimate as an untapped pool of available funds. Thus, the contractor

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may be inclined to aggressively pursue these funds through changes and claims. Since contractors generally do not learn of the owner's estimate until after the bids are opened, contractors are presumed to regard any residual amounts between the low bid and the engineer's estimate as funds that have already been appropriated for the project. If this is the case, contractors may be more aggressive in pursuing changes and claims when the contract award amounts are less than the owner's estimated amounts (*4*).

Another measure of competitiveness on a project relates to the number of bids submitted. The inference is that a larger number of bidders will cause the low bid price to go down. One study noted a clear pattern that caused bids to be below the owner's estimate by 2 to 4 percent when at least six bidders competed on a project (*8*). Another researcher reported that each additional bidder contributed to a further decrease in the low bid on a project (*7*).

Other factors have also been identified as being associated with cost overrun rates. Inadequate site investigations or poor interpretation of the results of site investigations have given rise to increased cost overruns (*5*). Lack of consideration for the influence of existing utilities, right-of-way constraints, and drainage patterns have resulted in increased cost overruns (*9*). Poorly prepared contract documents, especially as related to scheduling requirements, time extensions, and differing site conditions, may result in increased cost overruns (*10*). Documents such as the technical specifications must be tailored to the project to avoid cost overruns (*11,12*). Similar comments have been made about ambiguous documents or conflicts between the plans and specifications (*13*).

RESEARCH METHODOLOGY

A study was conducted in which bid tabulations and cost information were reviewed and the sources or causes of cost overruns were investigated. The data were retrieved from projects completed for WSDOT. Although complete information was not available for all projects, in most cases information was compiled on such topics as project identification, project type, location of project (district), engineering effort involved (planning and construction), bidding information (bids submitted by each bidder), and cost history (engineer's estimate, award amount, and final cost). The data included 468 WSDOT projects undertaken from July 1985 through July 1989.

The data were analyzed to determine the degree of association between variables. Of particular interest was the degree to which selected variables were associated or correlated with the cost overrun rate. For this study, the cost overrun rate or overrun rate is defined as the amount (expressed as a percentage) by which the final cost of a project exceeds the original contracted amount. Analysis was conducted with the use of the Statistical Package for the Social Sciences (SPSS) using Kendall's correlation tests to evaluate the degree to which selected variables were related, and linear regression analysis was conducted to determine the extent to which project costs could be modeled.

RESULTS

The average cost overrun rate for the 468 WSDOT projects was 5.12 percent. Whereas there were some outliers, most project overruns and underruns were in the range of −20 to +40 percent (i.e., two projects had underrun rates below −50 percent, and four projects had overrun rates above +50 percent). One-third of the projects had final costs below the originally contracted or award amount. Ten percent of the projects had cost underrun rates below −7.5 percent. Cost underrun rates were encountered on projects in which the number of actual units on a unit price contract were below the engineer's estimate or in which deductive changes were made on the project. Twenty-five percent of the projects had overrun rates above 10 percent, and 10 percent had overrun rates above 18.5 percent. Because the data were relatively normal in distribution, when averages are presented in tabular form, the extreme outliers (below −50 percent and above +50 percent) are excluded to provide information that is more descriptive of "typical" data. With these outliers removed, the average cost overrun rate for the data was reduced from 5.12 to 4.68 percent. The average overrun rate in this study is considered to be 4.68 percent, which excludes the six extreme outlying values.

The project sizes ranged from as small as $37,000 to as large as $65,000,000. The average contracted amount was $1,866,000 (Table 1). The projects consisted of those completed between July 1985 and July 1989. For these projects, the average contract award amount was below the average of the owner's estimates by about 6 percent. On the other hand, the average of the final construction costs (contract award plus overruns) was very near the average of the owner's estimates. Thus, the overall history of the projects indicates that the owner's estimates are typically above the low bid or contract amount, but that they are a close approximation of the final costs to be experienced.

TABLE 1 Summary of WSDOT Project Construction Costs

Type of Cost	Number of Projects	Average Dollar Amount
Engineer's Estimate	468	$1,988,000
Contract Award	468	$1,866,000
Final Project Cost (Contract Award Plus 4.68% Overruns)	468	$1,992,000

Project Size

The projects represented in this study can be categorized as ranging from small to large. Since the median size of project was $625,000, most projects can be characterized as small. With the range of project sizes being large, comparisons could be made to determine the extent to which cost overrun rates were influenced by project size (Table 2). Results indicate, in general, that cost overrun rates tend to increase with increasing project size (correlation coefficient $= 0.28, p < 0.001$). A perfect correlation between variables would result in a coefficient of 1.0. The value of p is an indication of the probability that the association of the two variables is attributable to chance. Thus, a small value of p, typically below .05, is considered to be indicative of a statistically significant relationship.

Project Type

Cost overrun rates were examined to determine how they are related to the type of project. The four broad categories of project type included new construction, resurfacing (existing roadways), bridge (new and rehabilitation), and safety (safety improvements as traffic control or guardrails on existing roadways). Although no clear pattern of overrun rates was identified, it is apparent that in general the average engineer's estimate for each type of project was consistently above the average contract award amount (Table 3). The average of the engineer's estimates was above the average contract amount for resurfacing projects in all districts. For new construction projects and safety projects the same pattern was evident, with the exception of one district for each project type. The history in three of the six districts for bridge projects indicated that the engineer's estimates were below the actual contracted amounts.

Number of Bidders

It is often stated that the "lowest bidder is the contractor who made the biggest mistake." Whereas this is typically said in jest, there is some basis for the remark. It is generally assumed that the owner benefits from a lower price as the number of bidders increases for a particular project. The lower price is typically attributed to the increased competition. The existence of a larger number of bidders on a project generally is assumed to indicate that fewer projects are available for the qualified contractors. Thus, in an effort to maintain their construction volume, contractors are required to pursue construction projects more aggressively. Consequently, an increase in the number of bidders is often associated with a reduction in contract award amounts.

The data were examined to determine the influence of the number of bidders on various parameters. The number of bidders appears to increase with the size of the project (correlation coefficient $= 0.26$, $p < 0.001$). This trend was reasonably consistent for the data with the exception of those projects on which six or more bids were submitted. These projects tended to be slightly smaller than the average size of project on which five bidders compete. It appears that when the size of project approaches some given amount, fewer contractors are able to undertake the work (Table 4).

As postulated earlier, the number of bidders appears to be associated with the level of competition. The range of bids on each project was examined to see how this related to the number of bidders. It was determined that the range of bid amounts, expressed as a percentage by which the high bid exceeded the low bid, increased with the number of bidders (correlation coefficient $= 0.51$, $p < 0.001$).

The results indicate that the cost overrun rate tends to go up with the increase in the number of bidders. Only conjecture can be offered to explain this phenomenon. One explanation is that the larger number of bidders causes the competition to be keener and the bids to be noticeably reduced. If the bid was deliberately reduced to compensate for the increased competition, it is possible that the award recipients will have a greater incentive to seek compensation in excess of the contracted amount. Thus, the increased overrun rate associated with more bidders may not be a reflection of the influence of the bidders themselves, but rather that both are symptoms of a more competitive contracting environment. A contractor who has been awarded a contract based on an excessively reduced bid will possibly be more aggressive in "mining" the contract for sources of additional funds.

Range or Spread of Submitted Bid Amounts

When bids are evaluated, particular attention is often given to the extent of dispersion of the bid amounts. This dispersion,

TABLE 2 Project Size and Overrun Rates

Project Value (Average Value)	Number of Projects	Overrun Rate (%)
Under $250,000 ($132,000)	120	2.55
$250,000 to $500,000 ($354,000)	80	3.60
$500,000 to $1,000,000 ($719,000)	105	4.67
$1,000,000 to $2,500,000 ($1.52 Mil.)	102	5.93
$2,500,000 and Over ($9.66 Mil.)	62	7.91

TABLE 3 Engineer's Estimate and Contract Award by Project Type and District (Thousands of Dollars)

Project History	New Constr.	Resurfacing Projects	Bridge Projects	Safety Projects
DISTRICT 1				
Engr's Est.	*7,209	*651	938	*208
Award Amt.	6,611	603	975	201
(Number)	(59)	(48)	(11)	(34)
Overrun	7.84%	4.98%	2.75%	2.90%
DISTRICT 2				
Engr's Est.	*1,311	*927	*490	*200
Award Amt.	1,256	827	488	177
(Number)	(4)	(23)	(3)	(4)
Overrun	13.34%	1.46%	-5.12%	-5.86%
DISTRICT 3				
Engr's Est.	*3,828	*840	1,238	*222
Award Amt.	3,818	736	1,241	199
(Number)	(35)	(28)	(15)	(11)
Overrun	5.75%	3.44%	4.49%	-1.10%
DISTRICT 4				
Engr's Est.	*3,689	*875	*2,089	434
Award Amt.	2,847	867	1,908	489
(Number)	(8)	(27)	(14)	(4)
Overrun	4.68%	9.35%	3.96%	7.82%
DISTRICT 5				
Engr's Est.	3,226	*972	1,457	*224
Award Amt.	3,318	923	1,499	197
(Number)	(15)	(22)	(8)	(16)
Overrun	7.59%	4.83%	5.49%	5.30%
DISTRICT 6				
Engr's Est.	*2,311	*1,334	*688	*186
Award Amt.	1,974	1,202	582	162
(Number)	(7)	(32)	(10)	(6)
Overrun	2.59%	1.63%	4.64%	1.51%
ALL DISTRICTS				
Engr's Est.	*5,100	*897	*1,262	*218
Award Amt.	4,767	828	1,217	205
(Number)	(129)	(184)	(62)	(78)
Overrun	6.92%	4.30%	3.72%	2.47%

* Denotes where the average Engineer's estimate exceeded the average contract award.

or difference between the lowest and highest bidder, is often referred to as the "bid spread" and may be indicative of the clarity of the bidding documents, the nature of the competitive climate, the unknowns perceived to exist in a project, or some other variable that might cause bids to vary. For example, the submission of bids that are all closely clustered by several bidders might imply that estimating was consistent between bidders because of particular clarity in the bidding documents or that the bidders were consistent in their assessment of the cost to perform the work. Close clustering of bids is preferred by most owners.

If the bids are widely dispersed, some negative implications might be drawn. For example, a wide dispersion of bids might mean that some bidders were not serious competitors or that they deliberately submitted high bids to ensure high profits if they are awarded the contract. A wide range in bids might also mean that the bidders had different interpretations of the anticipated costs to construct the project. The differences might be the result of poor contract documents, projects that may be subject to differing site conditions, projects that might be undertaken in a variety of ways, or projects on which the number of unknowns as perceived by the bidders is high. A wide dispersion of bids leaves doubt for the owner about the true construction costs of the project.

From the results it is clear that the range of bids is related to the number of bidders (i.e., the range of bids increases as

TABLE 4 Influence of Number of Bidders on Project Cost Overruns

Number of Bidders	Number of Contracts	Avg. Contract Award Amount ($ Millions)	Range of Bids (% above low)	Overrun Rate (%)
1	13	.46	N.A.	5.61
2	85	.98	12.3	2.88
3	100	1.70	16.7	4.44
4	105	1.93	21.7	5.83
5	55	3.21	30.9	8.05
6+	93	2.24	33.5	3.00
All	451	1.88	22.44	4.66

the number of bidders increases). The range of bids is also associated with costs, because the cost overrun rate increases with an increase in the range of bids (Table 5).

When bids are considered, in addition to assessing the total dispersion of bids, particular attention is given to the difference between the lowest bid and the second-lowest bid. It is often surmised that if the second-lowest bid is close to the lowest bid, the contract award is made at a reasonable amount. On the other hand, if the second-lowest bid is considerably above the low bid, questions may arise as to the cause for the variation. Of considerable concern to the owner is the fact that the low bidder may have made an error in the preparation of the bid. A bidder who leaves a large sum of "money on the table" may elect to try to withdraw the low bid by claiming that an error of fact was made in the preparation of the bid. Even if the low bidder enters into a contract with the owner, the owner may be concerned about the possibility that the contractor will encounter financial difficulty on the project. Such problems for the contractor will usually adversely affect the progress of the construction project.

The bid data were examined with a particular focus on the difference between the low bid and the second-lowest bid, expressed as the percentage above the low bid. (Table 6). One clear pattern was that the difference between the low and second-lowest bids increases with the total range of the bids. However, this difference does not appear to be related to the number of bidders, nor is it clear how this difference relates to the cost overrun rate. The largest cost overruns appeared on projects that were smaller and had fewer bidders.

The existence of a relationship between the cost overrun rate and the amount of dispersion between the low bid amount and the average bid amount was assessed. The results indicate that no apparent relationship exists between the cost overrun rate and the difference between the low bid amount and the average bid amount.

Cost Overruns Attributed to Specific Contractors

It has often been stated by some WSDOT personnel that certain contractors develop reputations for "mining construction contracts" to extract every possible overrun from the owner. Although low bids submitted by these contractors will invariably result in cost overruns, the public policy of awarding contracts to the lowest bidder precludes the owner from disqualifying them for this reason.

It was presumed that contractors with such a reputation must undertake a significant number of WSDOT projects. The data were examined to identify contractors who had been awarded at least 12 construction contracts. Seven contractors that received at least 12 of the WSDOT contracts examined in the study were identified. (Table 7). Of these contractors, two were identified as having average cost overrun rates that were significantly higher than the overall sample rate of 4.68

TABLE 5 Influence of Range of Bids on Project Cost Overruns

Range of Bids (% above low)	Number of Bids (Avg.)	Number of Contracts	Avg. Engr's Est. ($Mil)	Avg. Award Amt. ($Mil)	Overrun Rate (%)
Up to 10%	2.98	100	2.25	2.20	3.82
10% to 30%	4.33	247	2.32	2.14	5.37
30% and over	5.78	93	1.10	1.00	6.42

TABLE 6 Influence of Difference Between Low Bidder and Second-Lowest Bidder on Cost Overruns

Difference Between Low and Second Low Bidder	Number of Projects	Overrun Rate (%)	Number of Bidders	Contract Award Amt. ($Mil)	Range of Bids (%)
less than 2%	112	3.62	4.75	2.23	19.8
2% to 4%	73	4.72	4.81	1.97	20.9
4% to 6%	66	6.08	4.52	1.81	21.1
6% to 8%	55	4.52	4.15	1.62	21.2
8% to 10%	40	2.57	4.15	2.73	22.0
10% to 15%	55	6.27	3.96	2.22	26.8
15% +	51	4.67	3.17	0.42	33.2

TABLE 7 Cost Overrun Rates of Contractors with Several WSDOT Construction Contracts

Contractor Designation	Number of Contracts	Sum of All Contracts ($Millions)	Overrun Rate (%)
A	13	18.18	1.36
B	12	15.31	1.81
C	15	13.64	4.40
D	12	12.65	4.67
E	27	23.68	4.96
F	13	33.20	7.52
G	12	6.05	9.82

percent. These contractors, designated as Contractors F and G, accounted for 4.58 percent of the total dollar volume of the construction contracts completed between July 1985 and July 1989 and were associated with 7.48 percent of the amount spent on overruns. For their combined 25 construction contracts, Contractors F and G had cost overrun rates above the sample mean of 4.68 percent on 18 of their projects. By using the test of two means, only the cost overrun history of Contractor G proves to be significantly different ($p < .05$) from the sample mean.

Time Overruns

Just as cost overruns occur on construction projects, time overruns may also occur. Project duration is commonly quantified as the period beginning on the date stipulated in the notice to proceed and ending with the date of substantial completion of the project. Time overruns are defined as the ratio of the actual project duration less the original contract duration divided by the original contract duration, expressed as a percentage. It is possible to have a negative value in the event that the actual duration is less than the originally contracted duration. Information was available with which to compute the time overrun rates. They were compared with the cost overrun rates (Table 8). From the results it is clear that cost overrun rates increase with time overrun rates, and vice versa. Rather than implying a causal association between these variables, it is inferred that factors causing the costs of construction to go up will also tend to cause the time of construction to increase.

Regression Analysis

The results of the correlation tests indicated that several of the variables were related. An attempt was made to develop

TABLE 8 Cost Overrun Rates as Related to Time Overrun Rates on WSDOT Construction Contracts

Time Overrun Rate (%)	Number of Contracts	Cost Overrun Rate (%)
Less than -10	100	2.36
-10% to 0%	82	2.63
0% to +10%	66	6.27
+10% and over	104	7.78

a model in which all the variables were included. The intent of the model was to have a means of predicting cost overrun rates by using such information as the size of the project, the number of bidders, the range of the bids, and so forth. The results of the regression analysis yielded no viable model by which cost overruns could be predicted. For example, one attempt included the variables of overrun rate (dependent variable), size of project, number of bidders, range of bids, design hours, and the engineer's estimate. The R^2 value for this attempt was less than 0.02, a number far too small to yield any meaningful result. Numerous other combinations of variables were attempted with no greater success in predicting the overrun rates.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Results indicate that cost overruns tend to increase with an increase in project size. An increase in the number of bidders on projects is associated with an increase in the range or spread in the bid amounts, and this is associated with increased overrun rates. The difference between the low bid and the second-lowest bid does not appear to provide any measure by which cost overruns can be predicted. Whereas individual contractors may be associated with particular patterns of cost overruns, no general findings were noted. In general, it appears that cost overruns on WSDOT construction projects are modest. Although the average cost overrun rate on WSDOT projects is about 4.68 percent, the eventual total cost of these projects generally is near the engineer's original estimate. This occurs because the contract award amounts are typically below the engineer's estimates by about the same value as the overall overrun rate. Whereas overruns cannot be readily modeled or predicted, indications are that costs are controlled well on most projects. Despite the information obtained on 468 construction projects, the issue of overruns is more complex than can be explained by the introduction of a few simple variables. Little is explained by considering only such topics as the size of the project, the number of bidders, the range of the bid amounts, and other data that are available near contract award.

The research appears to indicate that some contractors are more likely than others to be associated with cost overruns. It also appears that cost overruns may be associated with or related to the particular districts in which the projects are performed. It is not clear whether there are unique practices in given districts, the site conditions in different jurisdictions have a varying influence on overrun rates, or the individual personalities of contracting personnel influence overrun rates. To successfully answer these inquires, an in-depth study of considerable magnitude would have to be conducted. Such a study, if conducted through the cooperative efforts of several states, could be informative in further defining the factors that influence cost overrun rates on state highway projects.

Individual state agencies might also conduct internal studies to further investigate the sources of cost overruns. Such studies should be carefully formatted to ensure that all available information is documented. Of particular importance is the documentation of the sources of cost overruns. That is, cost overruns should be categorized by the cause of the cost increase (differing site conditions, changes, delays, etc.). If the sources of the cost overruns are identified, the cost overruns can be modeled, and they are then much more subject to being controlled.

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Final Evaluation of the Florida Department of Transportation's Pilot Design/Build Program

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Interest in design/build as an alternative contracting method is growing. Results of a pilot design/build program undertaken by the Florida Department of Transportation are presented. Project performance results were measured and compared with non–design/build projects during the same period. Significant improvements in project performance were realized. Results of a survey of all participants are included. Final evaluation and suggestions for improvement are given.

In the late 1980s the design/build contracting system gained increased attention from many construction contracting organizations. Construction contracting authorities began to examine new contracting methods that departed from the traditional low bid model. The state of Florida also recognized the potential value of a design/build contracting system to its public works construction program. Consequently, on June 30, 1987, the Florida legislature passed a new law authorizing the Florida Department of Transportation (FDOT) to undertake a trial design/build program. The pilot program was to consist of projects accomplished by a combined design and construction contractor. The program was given a funding limit of $50 million.

After a considerable amount of study, FDOT put together a design/build contracting program, hoping to significantly improve upon its traditional non–design/build systems. Eleven projects covering a variety of construction categories were eventually awarded as design/build projects. The program appeared to be successful. However, as with many new concepts, the design/build program was controversial. The Florida Transportation Builders Association, Inc., a road builders contractor organization, strongly opposed the program. Political debate appeared to make the future of Florida's design/build program uncertain. Clearly, there was a need for an objective evaluation of the program results on the basis of quantifiable measures.

As a result, FDOT employed the University of Florida to conduct a study of the design/build pilot program (*1*). The study was to provide an impartial evaluation of the trial program and to suggest improvements. The results of this evaluation provide an interesting comparison of design/build project performance with that of the traditional low bid project.

Historically, a great deal of information in the form of opinion exists concerning design/build as an alternative contracting procedure. Examination of these reports provides little quantitative information on project performance.

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A study done by the Transportation Corridor Agencies listed several potential benefits of the design/build process: not-to-exceed pricing, transfer of liability, construction cost savings, and design-construction time savings (*2*). However, another study administered by the National Cooperative Highway Research Program failed to find any clear documentation to substantiate time and cost savings resulting from design/build (*3*). Furthermore, design/build quality was found to be closer to minimum requirements than conventional contracting methods.

In spite of the controversy and lack of quantifiable data, national attention is focusing on design/build as an innovative contracting method (*4*). A Transportation Research Board task force is currently attempting to encourage experimentation and demonstrations with this system (T. Deen, unpublished data). Although the Federal Highway Administration does not yet participate in design/build projects, it has begun to realize the need for innovative and improved contracting practices.

FDOT DESIGN/BUILD MODEL

The basic concept of design/build is that both the design task and the construction task are assigned to a single contractor. Combination of design and construction responsibility suggests several advantages. For example, construction knowledge and expertise should become a part of the design (*5*). Administration of the work may be easier when only one entity must be dealt with. Time savings may be realized, particularly if the construction can begin before completion of the design.

Although all design/build programs share the basic concept of combining design and construction, there are many variations in the method used to select the design/build contractor. In the U.S. Navy Newport design/build model, design/build contractors submit a price proposal before any design submission. Award is made solely on the basis of low bid. Following award, a complete design must be submitted for approval before commencing construction (*6*).

Other agencies, including the U.S. Air Force and the U.S. Army Corps of Engineers, have used a two-step design/build system (*7*). In this case design/build contractors first submit their proposed designs. A short list of acceptable designs is then prepared. The short-listed contractors are then invited to submit a price proposal. Final award is based on low bid.

FDOT has developed a modified one-step procedure, which includes several unique features. Prequalification is done only at one stage, and teams of both contractor and consultant are selected instead of individual selections being made. Before advertisement, a design criteria package is prepared by FDOT, and prospective design/build teams are required to submit a letter of interest setting forth their prequalifications. Applicants are evaluated on the basis of their experience and available resources. A certification and technical review committee (CTRC) determines the relative ability of each applicant to perform the required services and assigns a score. A short list of qualified applicants is then prepared.

The short-listed design/build firms are invited to submit both a technical and a price proposal. The technical proposal includes design and time information. Each proposal is evaluated by CTRC, and scores are assigned for the design and time elements. The total score includes points for the following categories: management and organizational qualifications, design, and project schedule.

The weight assigned to each of these categories varies from project to project. For example, design may be considered a more important element for a bridge project than for a resurfacing project. The proposed price is divided by the total score to obtain adjusted score. Final award is made to the bidder with the lowest adjusted score.

FDOT's design/build model contains three features that distinguish it from other design/build systems. First, the contractor's qualification score is made a part of the total score on the basis of which final award is made. Second, the contractor is required to propose a time for the project, which is a major factor in calculating the final score. Finally, the contractor is required to perform construction engineering and inspection for the project. The cost of these services is to be included in the cost proposal. Figure 1 shows the FDOT design/build selection process.

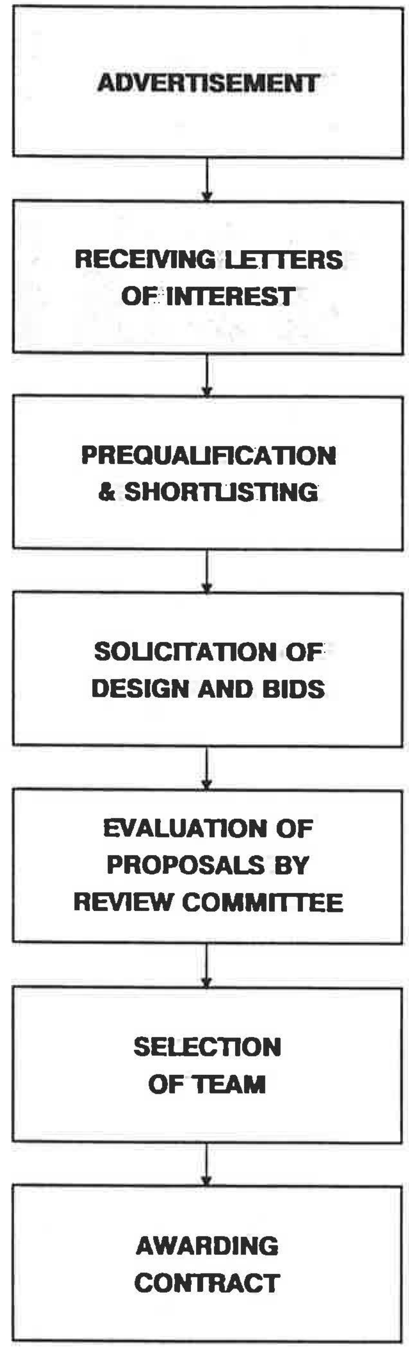

FIGURE 1 FDOT design/build procurement procedure.

COST PERFORMANCE EVALUATION

One troublesome aspect of evaluating design/build performance is that it is often difficult to directly compare design/build with non–design/build project performance. If a project has been accomplished as a design/build project, its performance can certainly be measured. However, what would have been the project performance if the same job had been accomplished as a traditional low bid project? Identical projects do not exist. Many variables, such as the contractor, the work season, and location, have a significant effect on project performance. Direct comparisons are in most cases not possible.

The approach used in this study has been to compare the mean performance measures of the design/build projects with the statistical mean performance measures of non–design/build projects. As far as possible, comparisons have been made using similar project categories such as size, type, and performance period. An attempt has been made to determine whether the average design/build results were significantly different from the average results obtained on non–design/build projects. Finally, if a difference is indicated, quantification of that difference has been attempted.

Table 1 presents the projects that have been accomplished under the FDOT design/build program. Original bid amounts are given in Column 4, and original bid times are given in Column 5.

FDOT uses a highly standardized cost estimating system to develop prebid estimates of cost. The estimating procedure accesses a data base of previously bid work activity unit prices. Estimates are prepared using quantities taken off the final design drawings and appropriate unit prices. Costs are adjusted for a variety of factors, including project location, time frame, and size.

Using the same estimating procedures as for traditional non–design/build projects, the FDOT estimating section pre-

TABLE 1 Design/Build Pilot Program Projects

Project (1)	Location (2)	Type of Project (3)	Bid Amounts (dollars) (4)	Bid Construction Time (days) (5)
Resurfacing SR 776 01050-3519	Charlotte County	Resurfacing	1,081,776	161
Resurfacing SR 13 78070-3519	St. Johns County	Resurfacing	1,785,000	240
Resurfacing SR 71 51020-3517	Gulf County	Resurfacing	1,385,765	180
Resurfacing SR 7 86100-3587	Broward County	Resurfacing	1,413,273	239
Resurfacing SR 91 97871-3322	Dade County	Resurfacing	2,912,936	210
Resurfacing SR 15 75080-3529	Orange County	Resurfacing	992,844	150
Bay Bridge 49040-3501 & 59010-3516	Ochlockonee County	Bridge	12,210,000	609
Turnpike FEC R/R 97940-3367	St. Lucie County	Bridge	1,888 206	540
Turnpike 97931-3310	Palm Beach County	Multilane	4,044,067	450
Const/Maint Office 11000-3511	Leesburg County	Building (FCO)	446,000	270
Turnpike Tolls Data Center 97931-3315	Palm Beach County	Building (FCO)	2,349,000	337

pared engineer's estimates of the design/build projects. Since final quantities are required, this type of estimate is normally prepared after the design is completed. Consequently, for the design/build projects the engineer's estimate could not be prepared until after the projects were awarded and the designs had been completed. Final quantities were generally not available until project completion. At the close of the study, quantities were available for seven of the design/build projects, and an FDOT engineer's estimate was generated for each. Budget figures were available for the projects that did not have an engineer's estimate. However, since the budgets were developed before design, they were not considered comparable with actual costs.

The engineer's estimate of cost was used as a baseline for establishing a cost comparison between the design/build projects and historical performance on non–design/build projects. FDOT maintains a historical data base of its engineer estimates compared with the low bids received. A review of these data provided an average difference between the FDOT engineer's estimate and the low bid. A summary of these data is presented in Table 2. It appears that the low bids received are somewhat below the engineer's estimates on the average.

Using this historical mean difference between the engineer's estimate and the low bid received, an expected low bid price was calculated for the design/build projects. Table 3 presents the adjustment of the engineer's estimated design/build project costs to an expected non–design/build low bid cost. Column 2 gives the engineer's estimate. Column 4 gives the expected low bid costs.

Since the design/build bid cost includes design, inspection, and construction, the non–design/build low bid cost had to be increased to include these costs. Estimates of design cost were developed from an analysis of 306 projects designed during the performance period of the design/build projects. Design cost on traditional projects averaged from 14 percent for projects costing less than $1 million to 6 percent for projects costing between $1 million and $10 million. The same procedure was used to develop an average historical construction engineering/inspection cost. Construction engineering/inspection costs were derived from an analysis of 395 projects performed during the design/build performance period. Table 4 summarizes FDOT's design costs and construction engineering/inspection costs.

These additional costs were added to the expected low bid

TABLE 2 Difference Between Low Bid and Engineer-Estimated Costs of FDOT Projects

Statistics (1)	Project Size Categories: Less than $100,000 (%) (2)	$100,000 to $250,000 (%) (3)	$250,000 to $500,000 (%) (4)	$500,000 to $1,000,000 (%) (5)	$1,000,000 to $3,000,000 (%) (6)	Greater than $3,000,000 (%) (7)
Mean	-14.7	- 4.0	- 6.1	-14.9	- 9.1	-10.3
Minimum	-46.3	-39.7	-27.6	-44.5	-38.1	-30.6
Maximum	26.3	23.1	16.9	28.0	26.4	15.9
Average Above	8.9	8.5	9.4	29.1	9.0	7.0
Average Below	-17.8	-13.0	-12.9	-17.7	-13.2	-14.4
Total Observations	52	33	36	34	59	53

NOTE: Based on the summary of FDOT statistics for 1990.

TABLE 3 Adjustment of Engineer's Estimated Design/Build Project Cost to Probable Non–Design/Build Low Bid Cost

Project (1)	Engineer's Estimate (Construction Cost Only) (dollars) (2)	NDB Probable Low Bid: Adjustment Factor (%) (3)	NDB Probable Low Bid: Construction Cost (dollars) (4)	Design and Inspection Adjustment Factor (%) (5)	Probable NDB Low Bid Total Cost (Including design and inspection costs) (dollars) (6)
Resurfacing SR 776 01050-3519	979,786	-14.9	833,798	+25.38	1,045,416
Resurfacing SR 13 78070-3519	--	--	--	--	--
Resurfacing SR 71 51020-3517	1,112,454	- 9.1	1,011,221	+25.38	1,267,869
Resurfacing SR 7 86100-3587	1,332,729	- 9.1	1,211,451	+25.38	1,518,917
Resurfacing SR 91 97871-3322	2,935,278	- 9.1	2,668,168	+21.3	3,236,488
Resurfacing SR 15 75080-3529	620,105	-14.9	563,675	+25.38	706,736
Bay Bridge 49040-3501 & 59010-3516	11,452,183	-10.3	10,272,608	+15.3	11,844,317
Turnpike FEC R/R 97940-3367	--	--	--	--	--
Turnpike 97931-3310	--	--	--	--	--
Const/Maint Office 11000-3511	390,729	- 6.1	366,894	+31.04	480,778
Turnpike Tolls Data Center 97931-3315	--	--	--	--	--

TABLE 4 Design, Construction Engineering, and Inspection Costs as Percentage of Total Project Costs for FDOT Projects

Project Size Categories (dollars) (1)	Design Cost (%) (2)	Construction Engineering and Inspection Cost (%) (3)
$250,000 to $500,000	17.04	14.0
$500,000 to $2,500,000	11.88	13.5
$2,500,000 to $10,000,000	12.0	9.3
$10,000,000 to $15,000,000	9.3	6.0

NOTE: 1) CEI costs (3) based on job charges for projects completed in fiscal years 88/89 & 89/90.
2) Design costs (2) based on database sample of projects completed in fiscal years 88/89 & 89/90.

cost to obtain a probable non–design/build low bid total cost. Column 6 in Table 3 gives the probable non–design/build total cost for the design/build projects.

A comparison of the actual design/build total cost is presented in Table 5. Three of the seven projects had a design/build cost greater than the estimated non–design/build cost. Four of the projects had a design/build cost less than the estimated non–design/build cost. The mean difference for all seven projects was a design/build cost 4.59 percent greater than an estimated non–design/build cost. However, one project appears to be an outlier in the data set. Resurfacing SR-15 resulted in a design/build cost 40.5 percent greater than the estimated non–design/build cost. Discussions with the estimators and with the project participants have failed to resolve this difference. The source of the variation remains unexplained. However, the investigation detected no evidence indicating that the additional cost resulted from the design/build contracting system.

If the project that had a 40.5 percent cost difference is omitted, the average design/build costs is 1.39 percent less than the estimated non–design/build costs. Considering the data variability and the outlying data point, the results do not indicate a significant difference in total project cost between design/build and non–design/build projects. This analysis does not consider any possible differences in road user cost. Only direct construction, design, and inspection costs have been considered.

Figure 2 presents the results of a statistical hypothesis test to test the hypothesis that the mean difference between design/build cost and the probable non–design/build cost is equal to 0. The hypothesis could not be rejected at the 95 percent significance level (*8*).

TIME PERFORMANCE EVALUATION

The procedure used to evaluate time performance was to compare the actual design/build project time with an estimated non–design/build project time. This involved developing an estimate of the project time that would have been required if the project had been performed as a non–design/build project. Since the design/build proposals include both design and construction tasks, an allowance for design time was added to the non–design/build construction time estimate.

FDOT develops a normal construction time for each non–design/build project. This time is determined by applying normal production rates to the project activity quantities. For the traditional non–design/build projects, the normal time typically becomes the specified contract duration.

However, as might be expected, actual performance times vary significantly from the specified original normal times. An analysis of 823 non–design/build projects performed during the design/build program period indicated that the mean difference between the original and the actual times was 14.7 percent. That is, on the average, the actual construction time required was 14.7 percent more than originally allocated. The original times do not include allowances for weather or other legitimate changes to the contract.

An FDOT normal construction time was developed for each of the design/build projects. It was adjusted by the 14.7 percent mean difference found for non–design/build projects. Table 6 gives the adjustment of the normal construction time to probable non–design/build actual construction time. Column 4 in Table 6 gives the estimated non–design/build construction times.

Table 7 compares the design/build actual construction time with the estimated non–design/build construction times. Nine of the 11 design/build projects produced actual construction times that were less than the estimated time required to perform the project as a non–design/build project. Two of the design/build projects required more time than estimated for performing the projects as non–design/build projects. The mean of the design/build comparison was 21.1 percent. That is, on the average, the design/build construction time was 21.1 percent less than the predicted non–design/build construction time.

With regard to design time, the design/build actual design procurement time was compared with the normal time allotted by FDOT for non–design/build design procurement. Data were not available concerning variances in actual non–design/build design times compared with the normal times set for design procurement. However, officials at FDOT believe that the actual design times vary very little from the normal times.

TABLE 5 Comparison of Design/Build and Probable Non–Design/Build Costs

Project (1)	DB Bid Amount (dollars) (2)	Probable NDB Total Amount (dollars) (3)	Difference of DB & NDB: Amount (dollars) (4)	Difference of DB & NDB: Percent (%) (5)	Mean Difference (%) (6)
Resurfacing SR 776 01050-3519	1,081,776	1,045,416	36,360	3.48	
Resurfacing SR 13 78070-3519	1,785,000	--	--	--	
Resurfacing SR 71 51020-3517	1,385,765	1,267,869	117,896	9.3	
Resurfacing SR 7 86100-3587	1,413,273	1,518,917	-105,644	-6.95	
Resurfacing SR 91 97871-3322	2,912,936	3,236,488	-323,552	-10.0	4.59
Resurfacing SR 15 75080-3529	992,844	706,736	286,108	40.5	
Bay Bridge 49040-3501 & 59010-3516	12,210,000	11,844,317	365,683	3.08	
Turnpike FEC R/R 97940-3367	1,888,206	--	--	--	
Turnpike 97931-3310	4,044,067	--	--	--	
Const/Maint Office 11000-3511	446,000	480,778	-34,778	-7.23	
Turnpike Tolls Data Center 97931-3315	2,349,000	--	--	--	
		TOTAL DIFFERENCE	342,073	32.18	

Table 8 compares the actual design/build design procurement times with the times normally required for non–design/build design procurement. The design/build designs were procured in considerably less time than would have been required under the normal non–design/build system. On the average, the design/build designs were acquired in 54.0 percent less time than required for normal non–design/build projects.

Table 9 compares total project time for the design/build projects and predicted non–design/build projects. All of the design/build projects performed better than the expected non–design/build results. On the average, the total design/build project time was 35.7 percent less than predicted for performing the projects as traditional non–design/build projects.

A small sample *t*-test was performed to verify the existence of a statistically significant difference in means between the construction time results on the design/build projects and the non–design/build projects. The results of this statistical analysis are shown in Figure 3. The design/build construction time results were confirmed to be statistically greater than the non–design/build results at a 95 percent significant level. The lower bound of the 95 percent confidence interval is calculated to be 18.0 percent. In other words, the statistical analysis indicates that at a 95 percent level of significance the design/build construction time results were at least 18.0 percent better than the average non–design/build results.

SURVEY OF DESIGN/BUILD PARTICIPANTS

It was believed that quantitative evaluations may not tell the complete story. Therefore, participants in the FDOT design/build pilot program were surveyed to obtain additional input. The participant list included design consultant partners and road builder contractor partners of all design/build teams that had submitted letters of interest in response to FDOT design/build advertisements. This includes both successful and un-

OBJECTIVE:	To test if the mean percentage difference of Design/Build low bid and probable Non-Design/Build total cost is zero.
STATISTICAL DATA:	$\bar{y} = 4.59$ $n = 7$ $s = 17.32$ df = 6 (degrees of freedom = 7-1)
TEST:	H_o: $\mu = 0$ H_a: $\mu \neq 0$ TS: $t = \frac{\bar{y} - \mu_o}{s/\sqrt{n}} = 0.7$ RR: $t_{\alpha/2} = 2.447$ (for $\alpha = 0.05$ & df = 6)
RESULT:	Since 0.7 < 2.447, therefore do not reject null hypothesis.
CONCLUSION:	At 95% confidence level it can not be concluded that mean percentage difference is not zero.
CONFIDENCE INTERVAL:	At 95% level Min = -11.43, Max = 20.61.

FIGURE 2 Hypothesis testing for design/build costs.

TABLE 6 Adjustment of Normal Construction Time to Probable Non–Design/Build Actual Construction Time

Project (1)	Normal Construction Time (days) (2)	NDB Adjustment Factor (%) (3)	Probable NDB Actual Construction Time (days) (4)
Resurfacing SR 776 01050-3519	270	14.7	310
Resurfacing SR 13 78070-3519	270	14.7	310
Resurfacing SR 71 51020-3517	270	14.7	310
Resurfacing SR 7 86100-3587	270	14.7	310
Resurfacing SR 91 97871-3322	365	14.7	419
Resurfacing SR 15 75080-3529	270	14.7	310
Bay Bridge 49040-3501 & 59010-3516	1,000	14.7	1,147
Turnpike FEC R/R 97940-3367	365	14.7	419
Turnpike 97931-3310	365	14.7	419
Const/Maint Office 11000-3511	365	14.7	419
Turnpike Tolls Data Center 97931-3315	420	14.7	482

TABLE 7 Comparison of Design/Build Actual Construction Time with Probable Non–Design/Build Actual Construction Time

Project (1)	DB Actual Construction Time (days) (2)	Probable NDB Actual Construction Time (days) (3)	DB and NDB Time		Mean Difference (%) (6)
			Difference (days) (4)	Difference (%) (5)	
Resurfacing SR 776 01050-3519	154	310	-156	-50.3	
Resurfacing SR 13 78070-3519	279	310	-31	-10.0	
Resurfacing SR 71 51020-3517	200	310	-110	-35.5	
Resurfacing SR 7 86100-3587	225	310	-85	-27.4	
Resurfacing SR 91 97871-3322	218	419	-201	-47.9	-21.1
Resurfacing SR 15 75080-3529	229	310	-81	-26.1	
Bay Bridge 49040-3501 & 59010-3516	536	1,147	-611	-53.3	
Turnpike FEC R/R 97940-3367	570	419	151	36.0	
Turnpike 97931-3310	527	419	108	25.8	
Const/Maint Office 11000-3511	253	419	-166	-39.6	
Turnpike Tolls Data Center 97931-3315	462	482	-20	-4.1	
TOTAL DIFFERENCE			-1,202	-232.4	

successful proposers. A total of 74 participants were surveyed, and 32 responses were obtained.

A summary of the survey data is shown in Figure 4. The results of questions covering the most significant issues are as follows:

1. Fifty-three percent of the respondents found the design criteria furnished by FDOT to be satisfactory. Thirty-seven percent found it to be not sufficient. Ten percent thought it was overly restrictive.
2. Seventy-five percent of the respondents found FDOT's evaluation and scoring procedure to be appropriate.
3. The respondents ranked the project categories in terms of suitability for the design/build method as follows, in order of highest to lowest suitability: building structures, bridges, resurfacing, and multilane.
4. Ninety-four percent of the respondents believed that FDOT should subsidize a portion of the design cost for the unsuccessful short-list participants.
5. Sixty-six percent of the respondents found that the design/build system resulted in reduced construction time.
6. Seventy-two percent of the respondents found setting their own construction time to be beneficial.
7. Seventy-four percent of the respondents indicated that FDOT's design/build program should be continued with changes. Ten percent indicated that it should be continued as is. Sixteen percent believed that it should be discontinued.

This input from the design/build participants appears to indicate a generally favorable response to the program. Very small differences in responses could be detected between design consultant and contractor participants. For example, 73

TABLE 8 Comparison of Normal Design/Procurement Time with Design/Build Design/Procurement Time

Project (1)	DB Design/ Procure- ment Time (days) (2)	Normal Design/ Procure- ment Time (days) (3)	Design/Procurement Time Difference (days) (4)	Design/Procurement Time Difference (%) (5)	Mean Difference (%) (6)
Resurfacing SR 776 01050-3519	134	300	-166	-55.3	
Resurfacing SR 13 78070-3519	133	300	-167	-55.7	
Resurfacing SR 71 51020-3517	132	300	-168	-56.0	
Resurfacing SR 7 86100-3587	138	300	-162	-54.0	
Resurfacing SR 91 97871-3322	134	300	-166	-55.3	-54.0
Resurfacing SR 15 75080-3529	132	300	-168	-56.0	
Bay Bridge 49040-3501 & 59010-3516	229	420	-191	-45.5	
Turnpike FEC R/R 97940-3367	139	300	-161	-53.7	
Turnpike 97931-3310	146	300	-154	-51.3	
Const/Maint Office 11000-3511	127	300	-173	-57.7	
Turnpike Tolls Data Center 97931-3315	138	300	-162	-54.0	
TOTAL DIFFERENCE			-1,838	-594.5	

percent of the contractors, who are usually uncomfortable with subjective award procedures, found the evaluation method appropriate. Seventy-seven percent of the designers answered the same question positively.

SUMMARY AND CONCLUSIONS

FDOT has completed a trial design/build program consisting of 11 projects with a total contract value of $30,508,867. The project performance results for these trial design/build projects have been measured and compared with the average performance obtained on FDOT's non–design/build projects during the same period.

An analysis of the cost performance information indicated that the average design/build direct cost was 4.59 percent greater than the average non–design/build cost. However, statistical analysis of the data failed to confirm this difference in means. Because of the small sample size (seven) and the data variability, the result of the direct cost comparison is inconclusive.

Comparison of project time performance results provided a more definite indication. The average design/build construction time was 21.1 percent less than the average for non–design/build projects. Statistical analysis indicated with a 95 percent degree of certainty that the design/build average construction time was at least 18.0 percent less than the non–design/build average construction time. Actual design/build design procurement times were also considerably less than the normal design procurement time for non–design/build projects. The average design/build design time was 54 percent less than the normal time allocated for non–design/build design procurement. The savings in project performance time means that for the 11 design/build projects an additional 3,040 project days would probably have been required if the projects

TABLE 9 Comparison of Total Design/Build Time with Probable Total Non–Design/Build Time

Project (1)	Total DB Time (days) (2)	Total Probable NDB Time (days) (3)	Total Project Time Difference (days) (4)	Total Project Time Difference (%) (5)	Mean Difference (%) (6)
Resurfacing SR 776 01050-3519	288	610	-322	-52.8	
Resurfacing SR 13 78070-3519	412	610	-198	-32.5	
Resurfacing SR 71 51020-3517	332	610	-278	-45.6	
Resurfacing SR 7 86100-3587	363	610	-247	-40.5	
Resurfacing SR 91 97871-3322	352	719	-367	-51.0	-35.7
Resurfacing SR 15 75080-3529	361	610	-249	-40.8	
Bay Bridge 49040-3501 & 59010-3516	765	1,567	-802	-51.2	
Turnpike FEC R/R 97940-3367	709	719	-10	-1.4	
Turnpike 97931-3310	673	719	-46	-6.4	
Const/Maint Office 11000-3511	380	719	-339	-47.1	
Turnpike Tolls Data Center 97931-3315	600	782	-182	-23.3	
TOTAL DIFFERENCE			-3,040	-392.6	

had been accomplished under the traditional non–design/build method.

The design/build projects also produced a significant reduction in after-bid changes to the contract. The design/build program projects had an average change amount of 4.09 percent. FDOT's non–design/build projects for 1990 had an average change amount of 8.78 percent. This improvement suggests enhanced constructibility and designer-constructor interaction.

A survey of participants suggested that the program was generally well received. The majority of respondents, including contractors, indicated that the design/build program should be continued. In spite of the subjective nature of the award evaluation procedure, a majority of respondents including contractors believed that the evaluation method was appropriate.

Do these dramatic improvements in performance result from the combining of the design and construction functions within a single contract entity? Probably not entirely. There may be other features of FDOT's design/build model that contributed to the program's success. Qualification standards have been maintained at a high level. Therefore, the qualified participants are exceptional contractors and designers. Better-than-average performance would appear to be expected. Inclusion of the project time as a major award scoring criterion certainly establishes an incentive to reduce performance time. Furthermore, the selection of the projects to be done as design/build may introduce some bias.

These considerations should not detract from the program's apparent success. FDOT's pilot program has demonstrated that design/build can produce improved project performance. Design/build is an important contracting alternative.

OBJECTIVE: To test if the mean percentage difference of original construction time and actual construction time for Design/Build (DB) Projects is significantly greater than Non-Design/Build (NDB) Projects.

STATISTICAL DATA:

μ_o = 14.77 (population mean difference of NDB)

$\bar{y}$ = 9.47 (sample mean of 11 DB projects)

n = 11 (number of DB projects)

s = 33.02 (standard deviation of difference)

df = 10 (degrees of freedom = 11-1)

TEST:

H_o: μ = 14.77

H_a: μ < 14.77

TS: $t = \dfrac{\bar{y} - \mu_o}{s/\sqrt{n}} = -2.43$

RR: t_α = 1.812 (for α = 0.05 & df = 10)

RESULT: Since |-2.43| > 1.812, therefore reject null hypothesis.

CONCLUSION: At 95% confidence level it can be concluded that sample mean is significantly greater than the population mean.

LOWER BOUND: Minimum = $t_\alpha\, s/\sqrt{n}$ = 18.04

FIGURE 3 Hypothesis testing for design/build construction time.

1) The design criteria given to the DB Team was --

Satisfactory	Not Sufficient	Overly Restrictive
53%	37%	10%
(16)	(11)	(3)

2) The proposal evaluation procedures and scoring were --

Appropriate	Not Appropriate
75%	25%
(21)	(7)

3) Rate the various projects with regard to their suitability for the Design/Build Program --

	Building Structure	Bridges	Resurfacing	Multi-lane
Highly Suitable	48%	34%	29%	3%
	(14)	(11)	(9)	(1)
Suitable	34%	44%	29%	52%
	(10)	(14)	(9)	(16)
Not Suitable	18%	22%	42%	45%
	(5)	(7)	(13)	(14)

4) Should the FDOT subsidize a portion of the proposal preparation cost for those bidders who are short listed and submit technical proposals --

Yes	No
94%	6%
(30)	(2)

5) Did the Design/Build System give you added ability to reduce construction time --

Yes	No
66%	34%
(21)	(11)

6) Was setting your own project time a beneficial feature of the Design/Build System --

Yes	No
72%	28%
(23)	(9)

7) The Design/Build Program should be --

Continued as is	Continued with changes	Not continued
10%	74%	16%
(3)	(23)	(4)

FIGURE 4 Summary of survey of design/build participants.

A review of the results of FDOT's trial design/build program suggests several observations concerning design/build.

First, the need for establishing high qualification standards should be balanced with the need to maintain a competitive construction market. If participation in the program is overly restrictive, competition will suffer. In FDOT's model, it may be more appropriate to establish a minimum prequalification standard. Once qualification is determined, each bidder would be evaluated solely with regard to design, cost, and proposed time. This may provide a more level playing field for the competitors and allow room for the newer and less-experienced participant.

Some compensation should be considered for nonsuccessful participants to cover at least part of their design costs. Without this subsidy the smaller designer may be unable to risk losing the investment in design cost. Therefore, competition may eventually be limited to only a few large participants. A reduction in competition sooner or later results in higher costs.

More study should be given to the question of which project categories are most suitable for design/build. Projects providing an opportunity for design innovation and contractor input into design appear to be good candidates. Projects where there is little design flexibility, such as repaving, probably are not the best design/build projects.

Design/build by its very nature is a contracting method that imposes some degree of restriction on competition. Contractors and designers are forced to find opposing partners. Depending on the prequalification standards, participation may be limited. For these reasons its use should be limited. Therefore, it is particularly important that design/build be used on projects in which the optimum benefit can be achieved.

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American Welding Society's Certified Welding Technician

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An overview of the requirements for the certification of technicians employed in the welding industry is provided. The education, experience, and examination requirements for certification are presented. The American Welding Society's program is a method for technicians to establish a record of their qualification and abilities in welding industry work.

The American Welding Society (AWS) is an organization of more than 39,000 members with the mission of advancing the science, technology, and application of welding. The structure of AWS includes 27 standing committees, which have differing specific responsibilities but collectively support the overall mission of the society.

One of the standing committees is the Qualification and Certification (Q & C) Committee. This body, composed of volunteers who represent a cross section of the welding industry, has the responsibility of developing specifications and requirements for certification of qualified personnel.

An important role of the society is the certification of individuals who demonstrate proficiency, knowledge, and skill in technical welding careers. In support of this essential function, the Q & C Committee has developed programs for the certification of welding inspectors, technicians, educators, and welders. Several of the programs are well established in this country and abroad, and the others are in the process of being introduced to industry.

Like all documents prepared by AWS, the certification standards are developed by volunteer committee members using a consensus ballot procedure. This process ensures that the requirements fulfill the needs of industry and are fairly applied to all participating parties.

Participants, both corporations and individuals, receive the advantages that a nationally recognized certification program provides. Employers are assured that their personnel have demonstrated their ability by successful performance in a standard examination format. Individuals receive recognition of their abilities, which is an impetus for professional pride and growth.

Since its formation in 1919, AWS has dedicated itself to advancing the science, applications, and technology of welding. Working through the volunteer committee structure of AWS, the Q & C Committee continues to develop certification programs that establish the minimum criteria necessary for the qualification of welding-related personnel.

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It is emphasized that AWS is guided by a volunteer base of members working by consensus to establish the various certification programs available to the welding community.

The basis for the establishment of a particular certification program is a survey of the industry that uses this particular individual. By using the data base available, from the membership or a specific industry, the survey can provide the usage, need, duties, tasks, and responsibilities of particular individuals.

The basis and documented need for the welding technician program began in 1976, when the Q & C Committee established five major areas of certification needs for the welding industry: welders, inspectors, technicians, laboratories, and educators.

Initially, the certified welding inspector was chosen to lead the field and provide guidance in the areas of safety, health, and expertise in this certification endeavor. Following were the AWS Certified Welders Standard and the AWS Standard for Accreditation of Test Facilities. Recently approved and published was the AWS Standard for Certification of Welding Educators. Each standard specifies the requirements and rationale for AWS certification in each field.

The Q & C Committee, after careful review of the data provided by individuals involved in the survey of welding technicians, believes that the welding technician program can provide the documentation necessary in the welding community.

AWS's Q & C Committee identified the welding technician as a critical certification program that is needed to communicate between welding engineers and production personnel. This level is perceived as the individual who works with the engineers in reviewing contracts, drawings, and technical literature and in preparing welding procedure specifications, procedure qualification reports, and production sequences. The technician is also a troubleshooter for production problems, the "go-between" for the welding engineer and production personnel. Therefore, the welding technician must be capable of effectively communicating with the engineer as well as production personnel. For problem solving, the welding technician must be capable of performing actual welding in the production environment.

AWS's Q & C Committee defines the welding technician as a person who determines weldment requirements from a specific code, standard, or specification. The welding technician either prepares or reviews written instructions for the production of weldments. The welding technician must be thoroughly familiar with various aspects of fabrication and assembly, including codes, standards, specifications, base materials, filler materials, heat treatment, mechanical properties, inspection methods, acceptance standards, tests, welder qualification requirements, fabrication tolerances, and welding process and procedures.

The welding technician shall also prepare and produce reports that reflect professional judgments (e.g., weld failure findings). For the welding technician to be effective, the activities performed shall be consistent with specified requirements and technical and ethical principles. The welding technician should be able to work with the professional engineer or a welder and appreciate the role of each in the development of weldments.

Responding to requests from American industry, a national survey was conducted in summer 1987. The results of the welding technician survey indicated that 74.8 percent of the 517 respondents would support a welding technician qualification/certification program.

The following summarizes the national survey's results:

1. Does your organization (select the most applicable)
   - A. Specify welding requirements (17.7 percent)
   - B. Make welding equipment/filler metal (10.4 percent)
   - C. Supervise and direct welding (13.8 percent)
   - D. Inspect or test welding (14.8 percent)
   - E. Consult concerning welding (16.6 percent)
   - F. Manufacture welded products (15.9 percent)
   - G. Other (please define) (10.9 percent)
2. Does your organization
   - A. Prepare written welding procedure specifications (36.4 percent)
   - B. Prepare drawings for weldments (18.6 percent)
   - C. Procure welding services (8.7 percent)
   - D. Qualify welders (20.1 percent)
   - E. Other (please define) (16.2 percent)
3. The position description
   - A. Meets your organization's needs (19.5 percent)
   - B. Defines a position used by your company (11.3 percent)
   - C. Misses the point (3.8 percent)
   - D. Is approximately accurate (38.4 percent)
   - E. Is not applicable to your company (27.0 percent)
4. Does your organization support the concept of qualification and certification of welding technicians?
   - A. Fully (36.6 percent)
   - B. Somewhat (17.9 percent)
   - C. Maybe (12.0 percent)
   - D. In some departments (8.3 percent)
   - E. Not required normally (21.5 percent)
   - F. It's total useless (3.7 percent)
5. Should the American Welding Society work in cooperation with the American Society of Certified Engineering Technicians?
   - A. Yes (42.2 percent)
   - B. No (10.4 percent)
   - C. No opinion (47.2 percent)
6. How much experience should an engineering technician have before applying for certification?
   - A. 1 year or more (17.2 percent)
   - B. 5 years or more (68.3 percent)
   - C. 7 years or more (10.7 percent)
   - D. 10 years or more (2.9 percent)
   - E. 15 years or more (1.0 percent)
7. Should a technician have been a certified welder?
   - A. Yes (33.0 percent)
   - B. No (7.2 percent)
   - C. Technicians' work can be done without the physical ability to weld (5.5 percent)
   - D. Welding ability is helpful but not needed (13.9 percent)
   - E. Welding ability is required but certification is not necessary (40.4 percent)
8. Does your organization use the technician as
   - A. Planner/preparer before work starts (7.6 percent)
   - B. Troubleshooter after the fact (12.9 percent)
   - C. About equally in both areas (79.5 percent)
9. What should be the minimum educational level required for a certified technician?
   - A. Eighth grade (2.3 percent)
   - B. High school or GED (73.3 percent)
   - C. Two years of college (24.4 percent)
10. Should an examination, like a professional engineers' examination, be used to certify technicians?
    - A. Yes (23.2 percent)
    - B. No (12.3 percent)
    - C. Yes, but directed at practical problems (48.5 percent)
    - D. A verified resume of satisfactory work experience is all that is required (16.0 percent)

As a result of the positive response to the survey from American industry, AWS's Q & C Committee initiated AWS QC-5, Standard for AWS Certification of Welding Technicians.

AWS QC-5 establishes the requirements for AWS certification of welding technicians. It describes how personnel are qualified, the principles of conduct, and practices by which certification may be maintained. It is intended that this standard supplement the minimum requirements of an employer, code, standard, or other documents. It is also intended that this standard will not be construed as a preemption of the employer's responsibility for the work or for the performance of the work performed by the welding technician.

AWS QC-5 established two levels of certification: "certified welding technician" and "certified welding technician in training."

The certified welding technician has the responsibility of directing operations associated with weldments that are completed in accordance with the appropriate contract documents, codes, and standards to produce a satisfactory product. The welding technician's activities begin before production work, continue through the production process, and do not end until after the production process is completed.

The certified welding technician in training has the responsibility of directing, under the direction of the certified welding technician, operations associated with weldments that are completed in accordance with appropriate contract documents, codes, and standards to produce a satisfactory product. The certified welding technician in training shall begin activities and continue through the production as directed by the certified welding technician.

A certified welding technician will be able to perform the following activities:

- The welding technician shall be capable of reading and interpreting drawings, specifications, and contract documents.
- The welding technician reviews the materials being specified to determine whether they comply with the requirements of the codes, standards, or other documents. The base materials and filler metals both require review for the weldability.
- The welding technician defines the appropriate welding processes and equipment to be used to comply with the written welding procedure specification. The welding technician shall be familiar with the welding process and understand the equipment inherent in that process. He shall verify that the fabricator or contractor is properly using equipment for the appropriate application. The welding technician should be capable of troubleshooting welding equipment.
- Written welding procedure specifications are required for most applications. The welding technician should review the specifications to determine whether they comply with the appropriate code, standard, or contract documents. The welding technician may write new welding procedure specifications. He may be required to define testing requirements to qualify welding procedure specifications. He should be responsible for preparing procedure qualification reports or review them for conformance to code, standard, or other documents.
- The welding technician may review the qualification data presented for welders, welding operators, and tackers to verify that they are properly qualified in accordance with applicable codes, standards, or contract documents. The welding technician should require requalification of welders if there is evidence that a welder's or welding operator's work does not conform to the applicable code, standard, or contract documents. The welding technician may specify tests that will properly qualify welders for the production.
- The welding technician reviews and verifies that the work being completed follows the instructions included in the welding procedure specification. She verifies that the joint preparation fit requirements comply with the drawings and welding procedure specifications. She reviews the use and control of filler metals in production facilities. The welding technician uses these reviews to correct problems.
- The technician shall be capable of performing informal visual inspections of the completed weldments for feedback information to determine whether they comply with the appropriate codes, standards, or contract documents. He examines the welds to ensure that they are the proper size, length, and do not have any discontinuities that exceed the acceptance criteria contained in various codes and contract documents that apply to the production work.
- The welding technician may verify that all required examinations of welds that are defined and specified have been completed. Various code standards and contract documents will require nondestructive or destructive examination of welds, including hydrostatic testing of vessels and other leak detection methods.
- The welding technician is responsible for clear and concise reports, records of reviews, inspection results, and performance data.

Required experience that a certified welding technician should have includes not less than 1 year of welding experience in the operation of welding equipment and 4 years of experience in an occupation function that has a direct relationship to weldments fabricated to a code or standard and directly involved in one or more of the following:

- Design—preparation of plans and drawings for weldments;
- Production—planning and control of welding materials, welding procedures, and welding oprations for weldments;
- Construction—fabrication and erection of weldments;
- Inspection—detection and measurement of weld discontinuities and verification of fabrication requirements; and
- Repair—repair of defective welds.

The required experience for certified welding technician in training will include not less that 2 years of experience in an occupation function that has a direct relationship to weldments fabricated to a code or standard and directly involved in one or more of the previously mentioned areas.

A high school diploma is the base educational requirement for both the certified welding technician and the certified welding technician in training. However, the standard contains provisions for educational levels less and greater than a high school diploma.

A written examination is required for the certified welding technician and the certified welding technician in training. A two-part examination consisting of welding technology fundamentals and a practical portion is proposed.

AWS will issue to each certified welding technician and certified welding technician in training applicant who complies with the requirements of the standard a serialized certificate and a wallet card stating that the applicant has met AWS's certification requirements. The certification will be valid for 4 years unless revoked for reasons defined by the standard.

In conclusion, AWS's program for certification of welding technicians has been developed to define minimum standards for persons performing these tasks and to provide a means of recognizing those who have the knowledge, qualification, experience, and expertise in the field of welding development, applications, and problem solving.

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