CONSTRUCTION DECISION SUPPORT SYSTEM FOR DELAY ANALYSIS

By J. K. Yates,[1] Member, ASCE

ABSTRACT: The Construction Decision Support System for Delay Analysis [delay analysis system (DAS)] for personal computers is a software program that adds the capability for determining possible causes for project delays and suggests alternative courses of action to prevent further delays. The DAS is not merely another scheduling software system; it is a program that is used with existing project-management software packages. Development of the DAS program could lead to the evolution of one "metaprogram" to address management issues. The expanded delay analysis system creates a logical-path form of managing human and material resources in construction, built upon the solid data (foundation) of actual industrial experience and need. This paper discusses industrial participation in the development of the delay analysis system program and describes the purpose and development of the program, its technical parameters, usage, and program output. A sample case study is presented that demonstrates how the program is utilized and the type of output it provides.

INTRODUCTION

The Construction Decision Support System for Delay Analysis [delay analysis system (DAS)] augments existing project-control software packages by adding the capability for determining possible causes for project delays and suggesting alternative courses of action to prevent further delays. The delay analysis system program integrates expert knowledge with existing control systems in order to streamline construction-delay analysis and decision-making processes. The purpose of the DAS system is to provide an auxiliary computer software program that processes information related to project delays (both current and historical).

The delay analysis system computer software program simulates the process of delay determinations by comparing technical parameters and accessing knowledge bases. Potential causes of delays are determined and the program generates suggestions for possible alternative courses of corrective actions to reduce delays. The delay analysis system is not merely another scheduling software. It provides information related to the causes of project delays that is not available in project-control software packages, and it is used to augment existing scheduling software packages.

In addition to each element of a project being monitored by project-management personnel, adequate feedback must also be provided to allow the selection of corrective actions in order to reduce or eliminate delays. The DAS program does not neglect human factors and judgments (which are required as an essential part of the analysis process); therefore, the program does not make decisions, but merely presents information required by managers to make more effective decisions, and it bases this information on the expert knowledge contained in the data bases.

A pilot prototype version of the DAS program was developed using

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reference data to determine project delays and the program was generated using a simplified programming language. Based on the success of the prototype program, further research was conducted to quantify additional causes of project delays and to capture the knowledge and expertise of construction professionals in an advanced version of the DAS program (Yates 1991). The next phase of the DAS program development involved the integration of additional data bases that address specific types of delays related to project and contract input parameters.

This paper discusses industrial participation in the development of the program and reviews existing programs and it describes development of the program, its technical parameters, and program output. Also presented is a discussion on the generation of industrial data for the knowledge-acquisition system, the development of the matrix of technical causes for delays, and the matrix of measures to reduce delays.

Industrial Participation in Program Development

Primary funding for this research project was received from the National Science Foundation. In addition, the research was also supported, or promoted, by three other industrial sources including the Business Roundtable, the U.S. Corps of Engineers, and story construction. The Business Round Table staff assisted in the development and distribution of the research surveys and provided contacts with construction user groups throughout the United States. All 50 U.S. Army Corps of Engineers district offices were contacted, and personnel from 35 of the district offices participated in the study. In addition, personnel from some of the district offices indicated their willingness to test the final version of the software.

Individuals from owner organizations, construction firms, construction-management firms, and the U.S. Corps of Engineers provided knowledge for the development of the data bases and their opinions on the delay analysis system (see the subsequent section headed "DAS Knowledge Acquisition") and provided comments on the viability of the program and its usefulness to their organizations. The individuals from the 115 firms contacted had neither used nor seen any programs that performed functions similar to the DAS program. In addition, many suggestions were provided on how the program could be expanded to accommodate additional information and submodels.

Review of Existing Programs

Research is being conducted at many different institutions related to the development of computer systems used in the construction industry in the area of project control, and specifically scheduling, that concentrate on different areas, including expert systems for determining activity durations, developing alternative logic for schedules, integrating cost control and scheduling, and improving existing scheduling techniques. One research investigation at the department of civil engineering of the University of British Columbia is developing a computer model of project delays based on data from one construction project. The University of British Columbia research is different from the DAS model, but the projects have coordinated information in order to avoid duplication of research efforts (Russell 1991).

Historically, scheduling research has focused on developing additions or changes to basic network algorithms in the area of resource leveling, fleet constraints, and resource-constrained scheduling. Although other research is being conducted to develop knowledge-based technology to monitor performance against established objectives and management criteria, the new techniques still rely on exception-reporting methods (*Project* 1987). Many of the scheduling systems currently being implemented, or researched, including project management review technique (PERT) and CPM, are based on management by exception principles (Barrie 1985; Jaari 1984). Management by exception involves the identification and isolation of critical or conflicting information related to a particular situation, which is relayed to the proper persons for consideration, decision, and action. In contrast, the DAS allows engineers and contractors to be more efficient managers, because it reduces crisis management and concentrates on project objectives (Monsey 1989; Yates 1991). Knowledge that is accumulated during the course of a construction project related to project delays is normally lost due to the inability to quantify it. The DAS assists in the quantification of this knowledge by its interactive capability and permanent data bases.

Other researchers are developing knowledge-based technology to guide managers in the production of the logic and data for planning purposes and to monitor performance against established objectives and management criteria. Several expert systems have been developed for construction planning and scheduling including a system for determining activity duration estimations, streamlining construction planning, developing applications of advanced computer technology to project controls systems, and systems for schedule updating (Hendrickson 1987a, b; Ibbs 1989a, b; Levitt and Kuntz 1985; Logcher 1987; Logcher et al. 1989). Logcher has been involved in integrating mainframe knowledge bases into personal computer (PC) systems; Nacichandra et al. (1988) have emphasized project network generation; and O'Connor et al. (1986) have concentrated on systems for the prediction of time for construction (Nacichandra 1987; O'Connor et al. 1986).

Most projects are being developed independently from existing commercial software systems that are in use by members of the construction industry and use declarative languages that require the use of special computers or artificial intelligence (AI) workstations (Moselhi et al. 1990). In contrast, the DAS program was developed as a decision-support system using a PC-based language (dBASE IV) for use on personal computers that interacts with existing project-control software packages.

Traditional project-management computer software does not address the determination of project delays or generate possible solutions for dealing with delayed activities. Most of the existing programs do not allow users to access information by type of project, specific location, or contracting parameters. Each of these parameters is important to the proper implementation and use of delay-analysis computer programs.

Purpose of DAS Program

The DAS program was designed to demonstrate the importance and utility of providing an interactive environment for knowledge acquisition to improve project controls and analysis processes. The development of an interactive system enhances information processing and decision-making abilities. The DAS program provides project managers and construction personnel with an integrated and intelligent system for providing clients, management, and other concerned parties with a consistent, detailed, and systematic analysis of a project at any point in time. The ability to not only monitor the progress of a project, but also to be able to determine possible causes

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of delays and corrective actions, provides a consistent evaluation of project performance.

The DAS program augments existing project controls systems by modeling a functional simulation of the construction environment. The functional processes that take place during schedule-analysis procedures have been computerized to capture the knowledge of experts in the field of project controls. The knowledge bases used within the program help generate evaluations that are normally performed manually and result in repetitious procedures. The computer program simulates the process of delay determinations by comparing technical parameters to the knowledge bases; once the potential causes of delays are determined, the program generates suggestions for possible alternative courses of corrective actions to reduce delays.

Background on Delay Analysis System

A project management knowledge engineering system [now called delay analysis system (DAS)] was developed to overcome the shortcomings of existing construction systems that integrate construction-control processes and construction automation. This program was based on previous research into the automation of scheduling processing (Rahbar and Spencer 1989; Rahbar et al. 1991). In 1991, the delay analysis (DA) system was expanded to include additional parameters and data bases (Yates and Rahbar 1991a, b; Yates 1991).

The technical dimensions of the DAS deal with schedules and cost control, but they could be extended to include data bases containing information on quality control, safety, and productivity. The DAS uses four indices, previously highlighted in the Construction Industry Institute publication *Project Control for Construction* (1987), for its technical parameters. The parameters include schedule evaluation indices, productivity factors, cost-performance factors, and critical-path-method (CPM) calculations.

In the construction industry, scheduling has become synonymous with CPM, and project-management packages provide the means for determining CPM calculations. However, focusing on project-management packages as the only management tool providing control at all projects levels is misleading. Project-management packages provide only one criterion (time) for evaluating schedule performance. The DA system extracts pertinent information from the project-management packages, but it is not exclusively dependent on them, because it compares this information to additional cost and scheduling data. An important benefit of a broader analysis model is the opportunity to verify schedule data.

Even when project managers are provided with the proper data required to perform schedule analysis, they do not always make the same analysis, even on similar types of projects. Many of the questions that should be posed are neglected; therefore, the DA system minimizes this problem by providing historical data specific to a particular situation and identifies tasks that require immediate attention. The program generates foremen-activity data sheets that are manually reviewed, and additional information is input into project specific data bases. The DAS program generates project-status reports that provide project-management personnel with narrative highlights of what problems are being encountered, possible causes of the problems, and several alternatives for corrective action.

The control phase establishes an information loop through the creation of new data each time a different course of action is implemented. These

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new ideas form the basis for the development of additional corrective measures. A pattern of relationships emerges between the data-collection mechanism and the summary-information reports.

Additional Features

In addition to using the delay analysis system to determine project delays, the system is being expanded to include submodels to assist in the equitable allocation of responsibility for project delays, a process that is usually undertaken during the resolution of construction disputes. Companies have used manual systems for quantifying responsibility for delays after the completion of construction, determining whether delays were caused by the owner or the contractor. This process is being incorporated into the DAS program to provide immediate retrieval of delay information. The concept of using the delay analysis system for dispute resolution was suggested by a researcher at the Construction Engineering Research Laboratory (CERL) investigating alternative dispute-resolution techniques.

Currently, during dispute-resolution processes, project delays are determined by comparing as-planned and as-built project schedules. Once the delays are identified, their origins and causes must be determined, which is usually accomplished by reviewing various construction documents such as requests for information logs, submittal logs, bulletin logs, changes orders, daily reports, project correspondence, and meeting minutes. After reviewing these documents, responsibility for delays are divided accordingly between the owner and the contractor. The DA system streamlines this process by providing historical data bases that can be accessed by a particular date during the project or by activity code number.

Development of DAS Program

The DAS program uses the dBASE IV programmer's language because this allows the DAS program to be compatible with, and to augment, Open Plan Scheduling Software. The program is also compatible with Primavera version 5.0. An investigation was conducted to identify what information systems are currently being used for the control of projects. A compilation of the number of project-management software packages sold was made for each software vender. An evaluation of existing project-control computer systems indicated that Open Plan and Primavera were the two leading software packages.

A major reason the software was first developed for use with Open Plan was that the U.S. Corps of Engineers began transferring their project-control systems to the Open Plan software package in 1991. As soon as Primavera released version 5.0, the DAS program was adapted to work with it. The DA system is also compatible with other project-control software packages, but some activity information has to be entered manually rather than being automatically extracted.

The program was designed for use by construction personnel with rudimentary computer skills. No special knowledge of specific computer software packages is necessary, because the program prompts users on what information is required and has simple choices and instructions for selecting which processes are desired. The data required by the program are available in existing project-management packages and no new data are necessary to run the DAS program.

To design the DAS program, relationships were formulated between decision variables, project-performance variables, and measurable outcomes. This analysis allowed a determination of information needs to be included in the project summaries. An influence diagram was developed for exploratory investigations of the decision-analysis structure and to assist in the development of the final version of the knowledge-acquisition system. Fig. 1 contains the eight submodels of the delay analysis program. The first three submodels are related to data entry; submodels 4 and 5 with processing-delay data; and submodels 6, 7, and 8 are used to summarize data, create historical data bases, and generate reports. Submodels 4 and 5 are discussed in detail in this section.

Technical Parameters of DAS Program

Activities that are behind schedule are highlighted during schedule analysis, but managers also need to know why an activity is delayed. Generic causes for project delays were identified and documented in research conducted by the construction Industry Institute by using key controlling factors, or drivers (*Project* 1987). The technical parameters currently accessed by the DAS program include schedule-evaluation indices, productivity factors, cost-performance factors, and critical-path-method calculations, were introduced in Construction Industry Institute research (*Project* 1987).

One of the most elementary forms of schedule evaluation is achieved by comparing what has been accomplished to the amount of work that was planned to be accomplished. This type of an evaluation is represented by the schedule performance index (SPI). The schedule performance index

$$\text{SPI} = \frac{\text{actual quantities to date}}{\text{scheduled quantities to date}} \quad (1)$$

is related to performance factors (PF) (which reflect construction efficiency), and these are used to measure the actual and planned productivity values

$$\text{PF} = \frac{\text{earned work} - \text{hours to date}}{\text{actual work} - \text{hours to date}} \quad (2)$$

A matrix was developed that analyzes the four possible permutations of SPI versus PF. The four quadrants in the matrix represent the following four

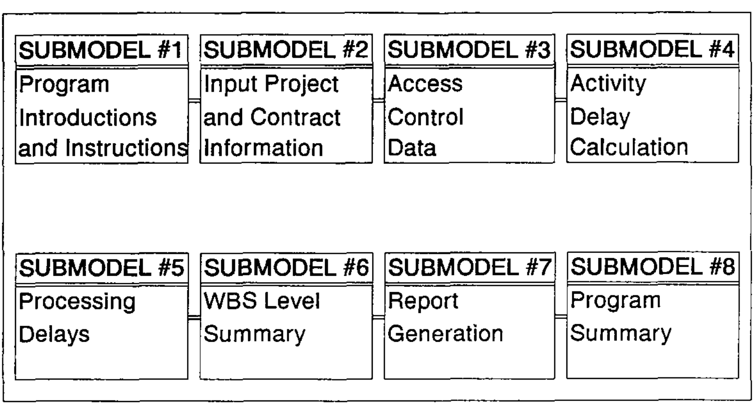

FIG. 1. Construction Delay Analysis System Submodels

scheduling and productivity scenarios: (1) Ahead of schedule, lower-than-planned productivity; (2) ahead of schedule, better-than-estimated productivity; (3) behind schedule, lower-than-planned productivity; and (4) behind schedule, better-than-planned productivity. Each of the quadrants is related to different causes of delays relative to the particular indices.

The DAS program was designed to interface with project-management software by downloading several technical parameters from project-management programs to the DAS program. The technical parameters are generated by the project-management software, the DAS program analyzes and integrates the technical factors, and these factors are related to a matrix of technical causes of delays. If an activity is behind schedule, the three controlling factors: (1) Total float; (2) schedule-performance index (SPI) (actual work to date/budgeted work to date); (3) and cost-performance index (CPI) (actual cost of work performed/budgeted cost of work performed), are calculated and possible causes of delays are determined based on combinations of these factors.

Total float, schedule performance indices, and cost-performance indices are related together in the technical-causes matrix by determining the permutations of TF $\geqslant$ or $<$ 1.0, schedule-performance index $\geqslant$ or $<$ 1.0, and the cost-performance index $\geqslant$ or $<$ 1.0. Each of the possible permutations is correlated, and the technical matrix summarizes and compares the different indices to determine whether an activity is progressing on schedule, needs attention, or needs immediate action.

In addition to listing what activities need attention and immediate action, the program accesses the computer knowledge bases and generates a list of potential causes for the delays and a list of possible alternative actions to assist in the decision-making process. Fig. 2 shows the detailed delay determination input-process-output (IPO) chart for submodel 4. The input box lists the parameters required to perform the process of determining the status of an activity. The process box describes the functions performed on the data. And the output box lists the results obtained from processing the data. Fig. 3 is the flow diagram for submodel 4, the delay-calculation submodel. This diagram shows how the data bases are linked to the processes and output.

DAS Knowledge Acquisition

To verify and supplement the technical causes of delays that were identified by the Construction Industry Institute in research on project controls for construction (*Project* 1987), a survey was developed as part of a National Science Foundation research project, whose report was entitled "A Knowledge Engineering System for Inquiry-Feedback Project Management" (Yates 1991).

Difficulties Encountered during Knowledge Acquisition

The knowledge bases were collected through an extensive survey of contractors, owners, and U.S. Corps of Engineers project-control personnel (a sample of the survey is not included, because of its length, five pages). Surveys were sent to 183 companies, and 115 individuals (response rate of 63%) returned them in the following proportions: Contractors, 39%; owners, 70%; and U.S. Corps of Engineers, 80%.

The knowledge-acquisition system collected information relative to eight different business sectors. The project categories covered and the percent-

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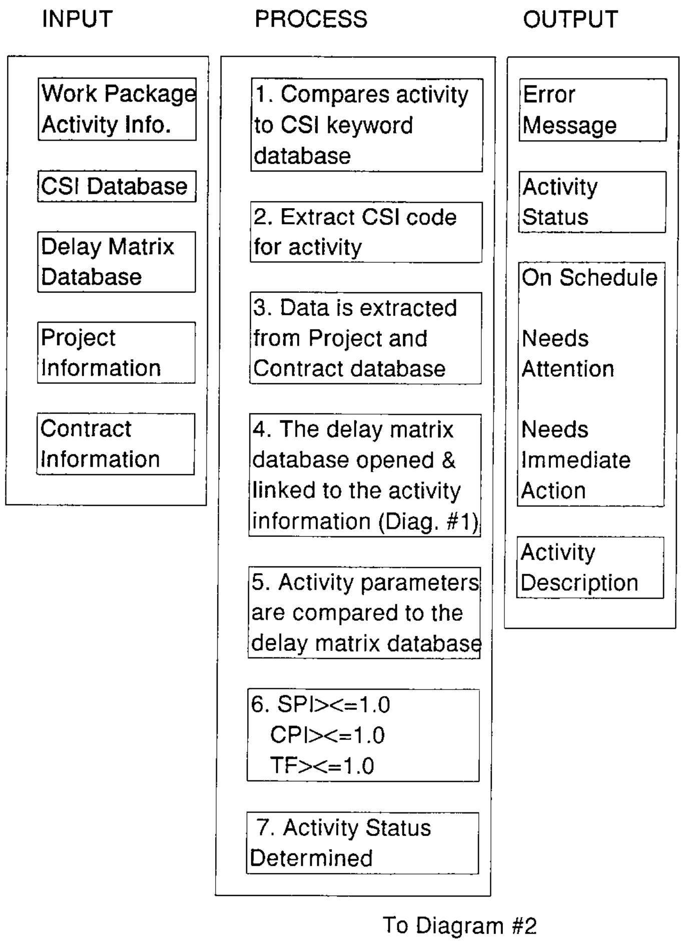

FIG. 2. Delay Determination Input-Process-Output Chart for Submodel #4

ages of the total represented by each type of business sector were the following: Commercial building 15%, process 28%, government 33%, power 2%, heavy industrial 6%, light industrial 5%, and infrastructure 6%. Many of the firms that listed process projects were also involved with power, heavy industrial, light industrial, and infrastructure, but in order to avoid duplication they were only listed under one type of designation.

A major difficulty in acquiring the knowledge required for creation of the data bases and the program was the development of the survey instrument. A pilot questionnaire was developed and distributed to five different firms for review, evaluation, and critique. The comments received during the preliminary testing of the questionnaire were incorporated into a revised version that contained changes in content, format, and wording of the questions. The revised questionnaire was sent out in three separate mailings. Separate mailings were used to increase the number of responses and to facilitate the inclusion of different types of firms. Using detailed cover letters and individual contacts within firms helped increase the overall response

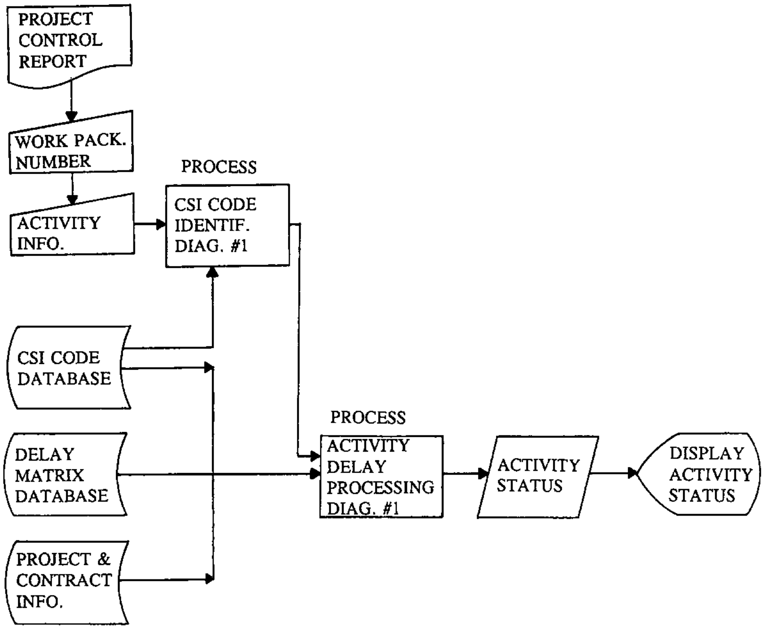

FIG. 3. Activity Delay Calculation Submodel #4

rate to 63% which was well above the normal average of approximately 27%.

Development of Data Bases

The knowledge bases were developed by building several different data bases—one for technical causes of delays, one for indicators of delays, and one for measures to reduce delays. The data base containing technical causes of delays was used to develop a "seeded" delay data base that was used in the program to provide sample delays. Table 1 contains a sample listing of the types of technical causes of delays that were input into data bases containing seeded delays. The seeded data base contains technical causes and measures to reduce delays that were obtained through the survey. The user can either access technical causes in the seeded data bases or extract data from data bases customized for their project that are developed as part of the interactive process.

The items listed in Table 1 were used to generate information on the causes for project delays relative to type of construction, type of contract, geographical location, and dollar volume of project.

Fig. 4 contains the attribute hierarchy and summary of the input parameters for delay submodel #5. Fig. 4 lists the different categories of data that are processed in submodel #5 (processing delays), including type of project, regional location factors, type of firm [engineering/procurement/construction (E/P/C)], type of contract, and contract value. This information is used to generate delays relative to the parameters indicated.

The data collected on the type of construction, type of contract, geographical location, and dollar volume was used to perform statistical tests to determine if there were correlations between technical causes of delays,

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TABLE 1. Sample of "Seeded" Delays in Technical-Causes-of-Delay Matrix

Category (1)	Delay (2)
Engineering	Inaccurate drawings
	Incomplete drawings
	Late engineering
Equipment	Equipment breakdowns
	Equipment delivery
	Improper equipment
	Shortage of equipment
External delays	Environmental issues
	Later than planned start
	Regulatory changes
	Permit approval
Labor	Craft shortages
	Labor productivity
	Labor strike
	Rework
Management	Construction methods
	More work than planned
	Quality assurance/quality control
	Schedule too optimistic
	Not working on critical tasks
Materials	Damaged goods
	Improper tools
	Material delivery
	Material quality
Owner	Change orders
	Design modifications
	Innaccurate estimates
	Owner interference
Subcontractor	Bankruptcy
	Subcontractor delay
	Subcontractor interference
Weather	Freezing
	Heat ahd humidity
	Rain
	Snow

indicators of delays, measures taken to reduce delays, and project parameters. The results generated by the statistical tests were used in the development of submodel #5. Because of the volume of information generated in the statistical analysis, data are summarized elsewhere (Yates and Khoury 1992).

The survey also contained specific questions related to the particular companies and individuals participating in the research. The questions were directed to solicit information on general company information—type of firm, dollar volume, etc; information on project team members; determining and ranking project objectives; designating those individuals involved in delay analysis; and the software and hardware used by the firms. This information was used to help develop the DAS software package and to tailor it to the needs of potential program users.

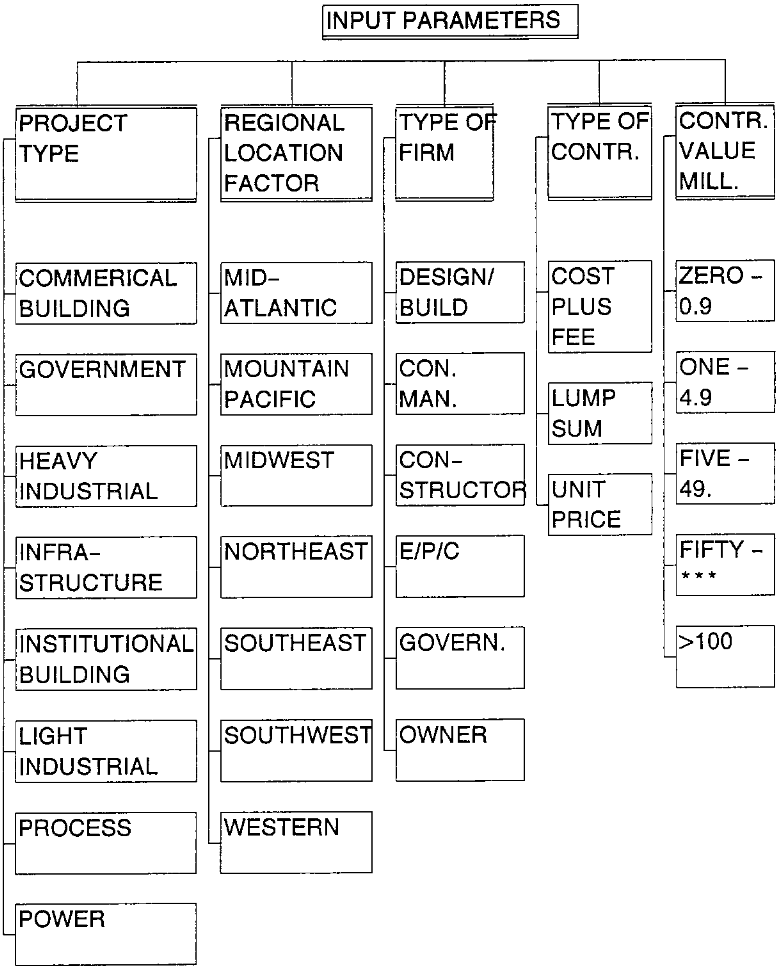

FIG. 4. Summary of Input Parameters for Delay Submodel #2

DAS Program Output

The construction-control phase involves the collection of project data that are synthesized by various project-control mechanisms and provides the basic evaluation systems required by the DAS program. The control process creates information loops because each time a different course of action is implemented the new data forms the basis for the development of additional corrective measures. A pattern of relationships emerges between data-collection mechanisms and the summary-information reports established by the program. Fig. 5 is the flow diagram for submodel #5 (processing delays). This diagram shows the information loop created to incorporate new data into the program and how the program allows for human interface during the generation of the foremen data sheets and user input of additional delays.

Submodel #5 generates several different categories of output. The main categories of information generated include list of possible technical causes

COMPANY INFORMATION

COMPANY NAME: WILLIARDS CONSTRUCTION COMPANY
COMPANY ADDRESS: 1410 WEST 47th ST.
CITY: WEST WILBURY **STATE:** WI **ZIP CODE:** 10374

PROGRAM USER (LAST, FIRST): WILSON, DANIEL
JOB TITLE: PROJECT MANAGER

TYPE OF FIRM:
___ OWNER
___ CONSTRUCTION MAN.
___ ENGINEER/MANAGE/CON.
_T_ CONSTRUCT ONLY
___ DESIGN/BUILD
___ OTHER:_____

PROJECT INFORMATION

PROJECT NAME: MALL COMPLEX
PROJECT ID NUMBER: 78493
PROJECT CONTRACT NO: 1237843
CLIENT: PLACER DEVELOPMENT CORPORATION

PROJECT MANAGER (LAST, FIRST): HALL, NATHANIEL
PROJECT CONTROLS SUPERVISOR: FIELD, ROBERT

PROJECT START DATE: 01/23/91
PROJECT COMPLETION DATE: 03/19/93

PROJECT TYPE:
_T_ COMMERCIAL BUILDING
___ GOVERNMENT
___ HEAVY INDUSTRIAL
___ INSTITUTIONAL BUILDING
___ OTHER:__________
__ PROCESS
__ POWER
__ LIGHT INDUSTRIAL
__ INFRASTRUCTURE

GEOGRAPHICAL INFORMATION

PROJECT LOCATION (CITY, STATE): WILLIAMSBURG, WV
LOCATION FACTOR:
_T_ URBAN-CENTER
___ SUBURBAN-CENTER
___ RURAL-TOWN
___ URBAN-PERIPHERY
___ SUBURBAN-PERIPHERY
___ RURAL-COUNTY

FIG. 6. Sample Input Screens for Submodel #2

of delays, list of alternative courses of actions for reducing delays, and list of measures suggested to prevent further delays.

The ultimate goal of the DAS program was to produce a concise summary of the status of a project by listing the following: Basic project data, key personnel, project status, possible causes of delays, and summary of possible corrective actions.

The status reports provide narrative highlights of the problems being encountered, possible causes of problems, the respective percentages for possible causes of problems, and several alternatives for corrective action.

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CONTRACT INFORMATION		
CONTRACT TYPE:	_T_ LUMP SUM	__ COST PLUS
	__ FIXED FEE	__ OTHER
LABOR TYPE:	__ UNION	_T_ NON-UNION
TOTAL CONTRACT VALUE:		$ 2.5 MILLION

MANAGEMENT INFORMATION

TYPE OF MANAGEMENT FOR THIS PROJECT:

_T_ PROJECT MANAGEMENT ONLY
__ PROJECT MANAGEMENT TEAM (TASK ORIENTED)
__ PROJECT MANAGEMENT TEAM (FIXED MEMBERS)

INDIVIDUAL RESPONSIBLE FOR DETERMINING CAUSES OF DELAYS:

_T_ PROJECT MANAGER	__ PROJECT ENGINEER
__ PROJECT ENGINEER	__ SCHEDULING ENGINEER
__ PROJECT CONTROL SUPERVISOR	

FIG. 6. ***(Continued)***

DAS Program Example

Fig. 6 shows sample input screens for submodel #2, which requires user input on project and contract parameters. The screens prompt the user to provide information in the following manner:

- Screen 1—Company using the program
- Screen 2—project specific information
- Screen 3—geographical information
- Screen 4—contract information
- Screen 5—management information

Once this information is manually input, it is stored and can be retrieved and edited or left unchanged. These data streams are used to access the proper delay data bases based on the different parameters provided. The data provided in submodel #2 are also used for the generation of summary reports.

A sample breakdown of the information processed in submodels #3, #4, and #5 is shown in Fig. 7. The first box, activities behind schedule, contains a partial list of activities that were determined to be behind schedule in this sample work breakdown level [work breakdown structure (WBS) is a method to organize a project by dividing it into different levels all the way down to specific tasks]. This example examines activity 21-350 (level two East Tower slab/columns). This activity was not completed, and only 32% of the work had been accomplished when the sample report was generated.

The second box (schedule analysis) indicates that the total float for activity 21-350 was negative 18 (18 days behind schedule), the schedule performance index (earned man-hours/scheduled man-hours) was 0.72, and the cost-performance index (cost earned/actual expenditures) was 0.95. By accessing the knowledge-information system (submodel #2); comparing to the rela-

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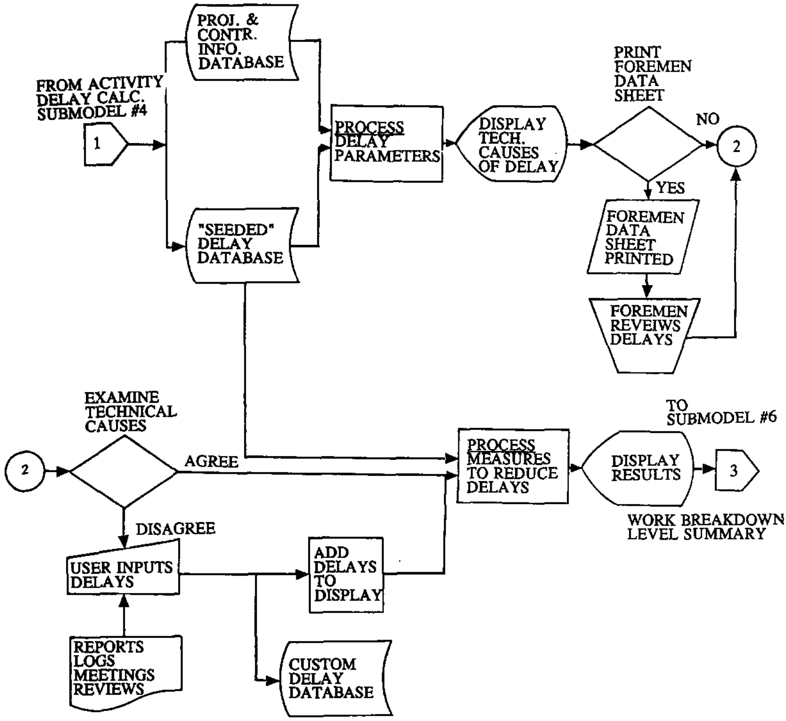

FIG. 5. Processing Delays Flow Diagram for Submodel #5

tionships between total float, SPI, and CPI (submodel #4); and relating these data to the technical-cause matrix (submodel #5), a list of possible causes was generated, shown in the third box, possible causes for delays. Since the total float was less than 1.0, the SPI less than 1.0, and the CPI less than 1.0, activity 21-350 fell into the category that required immediate action. Possible causes for this activity being delayed fell into the categories of design modifications, incomplete drawings, material problems, tool availability, and inspection delays.

These delays were printed on a foremen activity data sheet. During the review process these delays were confirmed and equipment availability was added to the list. Based on the knowledge bases, possible reasons for the delays were generated and listed in the fourth box (reasons for delays), which also included possible percentages for each of the delays. The fifth box (recommendations) is standard recommendations for actions to reduce the delays.

Fig. 8 contains a partial summary report for the sample project. The report summarizes project and contract information and includes causes for late items, late activities, recommendations, and upcoming milestones.

Testing and Validation of DAS Program

The DAS program was first tested by implementing a manual/computer prototype of the program on a complex construction project, a microbiology building on the campus of Iowa State University, from 1989 to 1991 (the

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1. ACTIVITY STATUS	
21-290 STRUCT SLAB ZONE A	NO PROGRESS REPORTED
21-300 COLUMNS ZONE A	DID NOT COMPLETE 50%
21-310 STRUCT SLAB ZONE B	DID NOT COMPLETE 90%
21-350 LEVEL 2 E. TOWER SLAB COL.	*DID NOT COMPLETE 32%*
21-400 LEVEL 3 E. TOWER SLAB COL.	DID NOT START

2. SCHEDULE ANALYSIS	
TOTAL FLOAT	= -18
SCHEDULE PERFORMACE INDEX (SPI)	= .72
COST PERFORMANCE INDEX (CPI)	= .95

3. POSSIBLE CAUSES OF DELAYS											
	O.K.			NEEDS ATTENTION				NEEDS ACTION			
	A	B	C	D	E	F	G	H	I	J	K
DESIGN MODIFICATIONS											X
INCOMPLETE DRAWINGS											X
MATERIAL PROBELMS											X
TOOL AVAILABILITY											X
INSPECTION DELAYS											X
CPM TOTAL FLOAT	>0	>0	>0	>0	=0	=0	=0	=0	<0	<0	<0
TOTAL WORK VOLUME (SPI)	>1	>1	<1	<1	>1	>1	<1	<1	>1	>1	<1
COST PERFORMANCE (CPI)	>1	<1	<1	>1	>1	<1	<1	>1	>1	<1	<1

4. REASONS FOR DELAYS	
LABOR STRIKE	0%
WEATHER	10%
ENVIRONMENTAL ISSUES	0%
REGULATORY CHANGES	0%
DESIGN MODIFICATIONS	20%
INCOMPLETE DRAWINGS	10%
EQUIPMENT DELIVERY	5%
MATERIAL PROBLEMS	15%
TOOL PROBLEMS	2%
QUALTIY CONTROL	0%
CRAFT LABOR SHORTAGE	20%
CONSTRUCTION METHODS	10%
OTHER	8%

5. RECOMMENDATIONS
WORK CRITICAL PATH ACTIVITIES
PROVIDE TEMPORARY HEAT
IMPROVE A/E COMMUNICATIONS
SEND AN EXPEDITOR TO THE SHOP
HIRE MORE CRAFTS
CONDUCT WORK METHODS IMPROVEMENT STUDIES

FIG. 7. Sample Output for Submodel #6

DELAY ANALYSIS SYSTEM STATUS REPORT

PROJECT:	FOUNDATION & STR. FRAMING SYS. INCLUDES DIV. 1,2,3,5,7,16
COST:	$2,500,000 LUMP SUM
SCHEDULE:	810 CALENDER DAYS FROM N.T.P. DATE TO JANUARY 23, 1991
KEY PERSONNEL:	
OWNER	PLACER DEVELOPMENT CORPORATION, WILLIAMSBURG, WV
C.M.:	P.M.: NATHANIEL HALL, P.C. SUP.: ROBERT FIELD
A/E:	
CONTR:	DANIEL WILSON, WILLARDS CONSTRUCTION COMPANY

PROJECT STATUS DATE: APRIL 14, 1992

LATE ITEMS: CAUSES	PREV. PD.	THIS PERIOD	TOTAL
INCOMPLETE DRAWINGS	18.0%	4.0%	22.0%
MATERIAL FAB./DELIVERY	10.0%	–5.0%	5.0%
TOOL AVAILABILITY	3.0%	–3.0%	0.0%
INSPECTION DELAYS	10.0%	–2.0%	8.0%
CRANE AVAILABILITY	8.0%	6.0%	14.0%
SHOP DRAWING APPROVAL	14.0%	4.0%	18.0%
MANPOWER SHORTAGE	25.0%	–5.0%	20.0%
WEATHER DELAYS	10.0%	–2.0%	8.0%
OTHER	2.0%	3.0%	5.0%
TOTAL	100.0%	0.0%	100.0%

LATE ACTIVITIES:	RECOMMENDATIONS:
* EXTERNAL BACKFILL	A/E REDUCE DWG APPROVAL TIME
– CIP TUNNEL	BETTER A/E COORDINATION
– START EAST WING	HAVE A/E REP. ON SITE
– LEVEL 3 EAST TOWER SLABS/COLS.	HIRE MORE CRAFT (IRONWORKERS)
* LEVEL 4 EAST TOWER SLABS/COLS.	IMPROVE WORKER PRODUCTIVITY
* ROOF SLAB EAST TOWER	REARRANGE MATERIAL LAYOUT
* LEVEL 2 WEST TOWER SLABS/COLS	REDUCE A/E BACKLOG
– ELECTRICAL DUCTBANKS	RENT SECOND CRANE
	SEND A REP. TO VENDOR'S SHOP
* ON CRITICAL PATH	WORK DOUBLE SHIFT

UPCOMING MILESTONES:	
FINISH EAST TOWER ROOF SLAB	MAY 6, 1992
START EAST TOWER MASONRY	APRIL 30, 1992
START EAST TOWER ROOF	JUNE 16, 1992
FINISH WEST TOWER ROOF SLAB	JULY 11, 1992
START WEST TOWER MASONRY	AUGUST 25, 1992
START WEST TOWER ROOF	NOVEMBER 8, 1992

FIG. 8. Sample Status Report for Submodel #7

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project was complex because of the requirements for unique laboratory utilities, protection, and special configurations). Using the prototype DAS program, a thorough analysis of the project was conducted. The results were compared to the procedures developed for the prototype program. One main reason for testing the DAS program on this particular project was that this project was experiencing extensive project delays, compounded by 21 separate prime contractors working at the site and being coordinated by one construction-management firm. The vice president of the construction management firm, Story Construction Company, worked closely with the researchers in assisting with the design of the delay analysis system.

The program was tested on the microbiology building project by monitoring delays on a weekly basis, generating delay analysis, and implementing corrective actions. When the program was first implemented, the schedule projected that the project would be four months behind schedule upon completion. The DAS program assisted management in circumventing potential delays and guiding the project back to its original schedule. Positive feedback on the implementation of the program was received from supervisors, foremen, engineers, and managers who participated in this project. The sample information provided in Figs. 7 and 8 was extracted during the testing of the program on this project.

In addition to testing the program on the microbiology building, the completed software package was tested by several individuals in the New York area. Different projects were modeled using the DAS software. The output generated included current as well as historical data bases containing project-delay information. Several of the respondents to the survey indicated that they would be interested in implementing the program and also in seeing it expanded for use on international projects. Several firms from the construction industry and U.S. Corps of Engineers offices have been contacted, and arrangements are being made for additional field testing of the program.

Advantages of DAS

One major advantage of the delay analysis system is the consistency introduced into decision-making processes. An interactive system that fully integrates the data-collection system of a project eliminates the requirement of handling the same data numerous times, which is important considering the vast amount of data generated by scheduling and control systems.

Another advantage of the delay analysis system is that it reduces the amount of time required to gather data for the dispute-resolution process upon completion of a construction project. The long process of apportioning equitable allocation of responsibility for delays would be reduced by the availability of computer data bases and the documentation provided by the delay-analysis program. Each time an activity is processed, the information is stored in a historical data base. The information can be retrieved either by date or activity code.

The program helps document decision-making processes, and a traceable link between collected project data and decisions is formed. Using the delay analysis system also allows managers to review decisions made under similar circumstances, which helps them to make more-informed decisions. It also furnishes managers with the proper tools for providing clients, top management, and construction personnel with accurate project-progress information.

As the delay analysis system is further developed the gathering and dis-

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pensing of information will be streamlined, roles of planning and policy-making will be modified, levels of uncertainty will be adjusted, and the overall philosophy of project management can be reexamined. Project-management systems should be designed to be flexible to accommodate the uniqueness of each project, its location, and its control management style; the DAS program demonstrates the importance of integrating computer systems with management methodologies.

Conclusions

This paper discussed the delay-analysis-system (DAS) program, industrial participation in its development, why it was developed, how is it used, the benefits of implementing it on construction projects, and provided sample outputs from the program. The delay analysis system augments traditional project-control systems and assists project managers in decision-making processes. The DAS integrates traditional project-control techniques with interactive methods to produce a program that not only monitors progress toward achieving project milestones, but also highlights causes for deviations from established baselines and provides recommendations as to how further delays can be prevented.

The information provided is in no way an exhaustive review of all of the capabilities of the DAS program; it was provided as a demonstration of some of the different capabilities of this type of program. The DAS program is continuously being refined. Hopefully, it will add innovative capabilities to the new generation of project-controls systems that are being designed.

Each delay in a construction project generates experience and expertise in recognizing and rectifying mistakes. This knowledge is costly to companies in time, labor, and safety as well as actual costs. This expertise can be accumulated, collated, and disseminated by the delay analysis system, thus giving future managers the benefit of experience without the cost of re-learning the same lessons on each project.

Appendix. References

Barrie, D. (1985). *Professional construction management.* McGraw-Hill Publishing Co., New York, N.Y.

Date, C. J. (1986). *An introduction to database systems.* Addison-Wesley Publishing Company, Inc., Reading, Mass.

Hendrickson, C. T., Marinellie, D., and Rehak, D. (1987a). "Hierarchical rule-based activity duration estimation." *J. Constr. Engrg. and Mgmt.*, ASCE, 113(2), 288–301.

Hendrickson, C., Marinellie, D., and Rehak, D. (1987b). "An expert system for construction planning." *J. Computing in Civ. Engrg.*, ASCE, 1(4), 253–269.

Ibbs, W. (1989). "Applications of advanced computer technologies to project controls." *Conf.*, National Science Foundation, Washington, D.C.

Ibbs, W. (1989). "A knowledge engineering approach to the analysis and evaluation of vertical construction schedules." *Conf.*, National Science Foundation, Washington, D.C.

Jaafari, A. (1984). "Criticism of CPM for project planning analysis." *J. Constr. Engrg. and Mgmt.*, ASCE, 110(2), 226–237.

Levitt, R. E., and Kunz, J. C. (1985). "Using knowledge of construction and project management for automated schedule updating." *J. Proj. Mgmt. Inst.*, 16(5), 57–76.

Logcher, R. (1987). "Adding knowledge based systems technology to project control systems." *Project Controls: Needs and Solutions; Proc., Specialty Conf.*, ASCE, New York, N.Y., 88–100.

Logcher, R., Wang, M.-T., and Chen, F. H.-S. (1989). "Knowledge processing for construction management data base." *J. Constr. Engrg. and Mgmt.*, ASCE, 115(2), 196–211.
Monsey, A. (1989). *Scheduling beyond network scheduling—investigating alternatives to CPM*. Washington University Press, St. Louis, Mo.
Moselhi, O., and Nicholas, M., Jr. (1990). "Hybrid expert system for construction planning and scheduling." *J. Constr. Engrg. and Mgmt.*, ASCE, 116(2), 221–237.
Navinchandra, D., Sriram, D., and Logcher, R. D. (1988). "Ghost: project network generator." *J. Computing in Civ. Engrg.*, ASCE, 2(3), 239–254.
O'Connor, M. J., De La Garza, J. M., and Ibbs, C. W. (1986). "An expert system for construction schedule analysis." *Expert systems in civil engineering*, C. L. Kostem and M. L. Maher, eds., ASCE, New York, N.Y., 67–77.
Project control for construction; publication 6-5. (1987). Construction Industry Institute, Austin, Tex.
Rahbar, F., and Spencer, R. (1989). "Automation of the scheduling process." *Trans.*, American Association of Cost Engineers, C3–C10.
Rahbar, F., Yates, J. K., and Spencer, R. (1991). "Project management knowledge engineering system." *J. Am. Assoc. of Cost Engrs.*, 33(7), 15–24.
Russell, A. D. (1991). "Automated daily site reporting." *Proc., Annual Conf.*, Canadian Society for Civil Engineering, Vancouver, British Columbia, Canada, Vo. III, 405–414.
Yates, J. K., and Rahbar, F. (1990). "Executive summary status report." *Trans.*, American Association of Cost Engineers, Boston, Mass., D3.1–D3.9.
Yates, J. (1991). "A knowledge engineering system for inquiry-feedback project management." *Progress Rep. to the National Science Foundation*, Washington, D.C.
Yates, J. K., and Khoury, T. (1993). "Construction delay analysis," MS thesis, Polytechnic University, New York, N.Y.