AUTOMATED CORRECTIVE ACTION SELECTION ASSISTANT

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ABSTRACT: Automated daily site reporting coupled with computerized data interpretation as an integral part of a project management system has the potential to be the missing link for effective construction project monitoring and control. This paper describes a schema to perform the automated interpretation of daily site records, to identify activities experiencing difficulties, to identify the source(s) of these difficulties, to identify the types of problems resulting, to find corroborating information from the daily site records, to validate the causes of these problems, and to suggest likely corrective actions. A framework is presented wherein each component of the analysis schema is defined. This framework includes a set of user-assigned activity-interpretation attributes, a set of problem sources, and a set of corrective actions. Expert rules are used to link these components, and fuzzy logic is used to define the imprecise relationships that exist between them. A prototype system has been developed to implement and test the schema (to be presented in a companion paper).

INTRODUCTION

This paper outlines the conceptual framework and reasoning used in developing a prototype system that automates selection of corrective actions for problematic activities in construction projects. (Implementation of this framework is addressed in a companion paper.)

Automated daily site reporting coupled with computerized data-interpretation can potentially become the missing link in monitoring and controlling construction projects. Many benefits of daily site reporting have been reported (Russell 1993). For instance, problematic trends can be detected more readily by maintaining daily site records, and timely corrective action can thus be initiated more quickly. To increase schedule credibility, automated schedule updating can be performed if activity status is recorded on a daily basis and used to update the schedule. Documentation of activity progress, problems encountered with activities, and environment, site, and workforce conditions is useful in preparing claims and as legal evidence. In addition, as each project is documented through daily site reporting, a company accumulates a knowledge base of experience that can be referenced for future projects.

All of these data form an image of the job through time. How useful these data are for purposes of explaining root problem sources, and thus identifying effective corrective actions is a function of the following: (1) The ability to standardize the classification of and accurately report field data; (2) the ability of management personnel to review and digest the lessons contained within masses of data; and (3) the ability to relate project variables

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such as environment conditions, site conditions, workforce data, and problem sources to activity performance.

At present, manual daily site reporting is performed on virtually all projects. The degree of rigor in reporting varies widely with few, if any, standards developed or enforced within individual firms. The challenge is to build on the existing requirement of daily site reporting in a way that provides a more standardized and comprehensive picture without increasing the reporting burden of site personnel. Achievement of this will provide a foundation for the automated detection of potential problems involving time, cost, scope, quality, and safety; and the sources of such problems. From this information, corrective actions to mitigate these problems can be determined.

No robust mathematical production functions exist, which might be useful in demonstrating performance sensitivity to changes in exogenous or endogenous variables for a diverse range of construction activities. The construction industry operates, instead, on numerous heuristic principles, rules of thumb, and knowledge that is often documented in memory rather than on paper. Some of this knowledge is remembered in patterns: the seasoned superintendent or project manager will have seen a troublesome situation before, and now, given the emergence of cues indicating a repetition of it, the superintendent attempts to avoid its consequences based on past experience.

To develop an automated system for dealing with problems, this knowledge and experience must be codified. Due to the imperfect understandings just described, tools such as fuzzy logic and expert systems could prove useful. Recent developments (Ayyub and Haldar 1984; Smith and Hancher 1989; Kouatli and Jones 1991) dealing with knowledge-based and fuzzy process control systems point the way to the automation of the interpretation of job records and the suggestion of corrective actions. For construction, such a system should be able to diagnose the following four issues: (1) That an activity, trade, or entire project is experiencing difficulty; (2) what the most likely causes of the difficulty are; (3) what corroborating information validates these causes; and (4) what the most appropriate corrective actions are.

In this paper we describe a framework for a computer-based system that possesses the foregoing diagnostic capabilities. Criteria guiding the design of the system include the desire for fast feedback (i.e. faster than the normal cost accounting and schedule updating cycles), the need for conceptual simplicity and robustness so that practical-sized projects can be handled, the ability to use data that can be collected with reasonable accuracy by human "sensors" and that is already being collected, at least in part, and a system architecture that allows for expansion and easy refinement in order to cope with an increasing and changing knowledge base and large-scale projects. The work builds on field experience, which provided a realistic view of how much information could feasibly be collected, and determined which information justified the amount of effort required to collect it. Field experience also demonstrated the need to train site personnel to record information in a useful yet straightforward manner.

LITERATURE REVIEW

The literature review revealed several studies on standardizing the measurement of productivity and developing functions and parameters to predict productivity and/or production rates. For example, Thomas et al. (1988)

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have developed a manual that describes a methodology for collecting and documenting the state or condition of various factors that have been reported to affect labor productivity. Thomas et al. (1990) outline a factor model that accounts for project, site, and management factors, and that contributes to the goal of developing formal methods of predicting site productivity as a function of project-specific characteristics. Nevertheless, no general methodology or universal set of functions has been described in the literature that predicts production rates or productivity in terms of work environment, site and workforce factors, the construction method selected, and the level of resources allocated.

Two systems are described in the literature that relate to the work described herein. The first, by Al-Tabtabai (1989) and Diekmann and Al-Tabtabai (1992), is a knowledge-based system that, using the methodology of earned value, identifies problems on the basis of performance measures that fall beyond acceptable thresholds. The approach makes use of a series of influence diagrams and related rules to infer causes of discrepancies. Then, using social judgment theory, the system forecasts expected performance of work packages at completion.

Rahbar et al. (1991) and Rahbar and Yates (1991) have developed an inquiry feedback system that uses schedule evaluation indexes, productivity factors, cost-performance factors, and critical path method (CPM) calculations to determine possible causes for project delays and to suggest alternative courses of action to prevent further delays.

Neither approach makes use of feedback or on-line data obtained directly from site operations (e.g. daily site report data). Off-line (e.g. cost-accounting data) as opposed to on-line information is used, which slows response time. The use of on-line data is one of the distinguishing features of the approach described herein.

Interestingly, no comprehensive listing of problem sources was identified in the literature, although some work in this regard is in progress (Yates, personal communication, 1992). Also, no references were found that focused on the documentation of corrective actions that could be adopted by project personnel, given a specific fact pattern that explains performance.

OVERVIEW OF CONTROL PROBLEM

Six steps for monitoring progress and implementing control in the corrective-action selection-assistant system are described in the following section. They are:

1. Define a base against which to monitor.
2. Select the items of information that are to be collected in order to monitor progress.
3. Design and calibrate the sensors.
4. Detect data in the field.
5. Interpret and analyze field data.
6. Diagnose problems and suggest corrective actions.

The first step is to define a monitoring base. The monitoring base consists of the subtrades, activities, extra work orders, and back charges scheduled for any given day. Additional activity data include forecast status, anticipated production rate, and trade responsible.

The second step is to select the information needed to monitor work progress. The information chosen is that contained in the daily site records of the automated daily site reporting system developed by Russell (1993). This information includes work environment data, such as weather and site conditions; workforce data for each trade involved in the job (e.g. number, skill, and turnover levels); daily activity status of all work scheduled (e.g. started, ongoing, finished, idle, or postponed); problem sources associated with activities (e.g. too much precipitation, insufficient/incomplete drawings) and the trade responsible for problem sources; and the time and cost impacts of problem sources on activities (e.g. days and man-hours lost, respectively).

The third step involves designing and calibrating the sensors to monitor progress. In contrast to many manufacturing processes that can be instrumented with sensors for automatically determining temperature, humidity, velocity, position, and so on, construction process sensors correspond to field personnel who record daily site information. Calibrating the sensors involves training personnel to report consistently, a task that is poorly done, if at all. The issues of sensors in construction is a fascinating one. Suffice it to say, for tracking all aspects of a project through time and space in continuously changing work environments, the human sensor will be the mainstay for observing and recording at the site in the foreseeable future. In time, the use of bar coding (Stukhart 1990), video (Eldin and Egger 1990), electronic weather stations, and other apparatuses will reduce dependence on human sensors for specialized measurement tasks.

The issue of detection in the field, the fourth step, contains the greatest degree of uncertainty and inconsistency. First, there is considerable variance in levels of education and experience as well as attitudes toward recording daily site information by field personnel (the field sensors). From recent experience on a typical heavy civil construction job, the cross section of site personnel responsible for recording daily site information ranged from those who are both experienced and educated (e.g. engineers), and willing to document work progress, productivity, delays, and problems, to those who are uneducated and have difficulty writing, and therefore struggle to document daily site information. Not only does the level of reporting skill vary among these people, but their willingness to record problems in the work also varies and is related to their tendency to align themselves with either the field or the office. Those that are "pro-field" and "antimanagement" tend to shun paperwork. On the other hand, as the number of subcontractors increases on a project, so too does the willingness of the general contractor's forces to record problems caused by these subcontractors. Detection and representation of information can be biased because, as often happens in construction, each party is interested in representing selective truth for their own benefit. All of these factors result in a great deal of variation in the quality of information collected in the field.

A second detection issue involves compiling a set of problem sources from which field personnel can choose; these choices must achieve a balance between being concise yet all-inclusive. The smaller the set of problems, the easier it is to select from it, yet the more likely it is that a problem will occur on the site that is not contained in the problem set.

Once data have been collected, the fifth step, interpretation, is necessary in order to derive benefits from the knowledge recorded. Automated interpretation is necessary if large amounts of data are to be analyzed quickly. Step six follows the analysis; problems interfering with work progress can be diagnosed and corrective actions suggested.

OVERVIEW OF SYSTEM ARCHITECTURE

An underlying premise of this work is that similarities exist between construction projects in the form of a recurring set of problem sources, problems, and corrective actions. In addition, most activities can be described in terms of a standard set of attributes. These sets of activity attributes, problem sources, problems, and corrective actions are incorporated as part of the system. By defining a body of knowledge that encompasses most projects, one does not have to specify such knowledge in each new case.

Automated interpretation is performed on an activity-by-activity basis in order to suggest, for activities encountering problems, corrective actions based on reported problem sources and recorded days and/or man-hours lost. An activity is defined both by its user-assigned and its system-derived attributes. User-assigned attributes include daily problem sources selected from a predefined set, with both time (days lost) and cost (man-hours lost) impacts. Furthermore, there exist project-wide conditions (workforce data, weather conditions, site conditions) that can be taken into account in diagnosing corrective actions for activities.

Problems of time, cost, quality, safety, and scope can arise out of a problem source (but at present, we have restricted our attention to the first three). In choosing corrective action(s) for an activity, each problem source must be examined. A set of corrective actions can be suggested based on an activity's attributes. Another set of corrective actions can be suggested by considering the type(s) of problem(s) arising out of the problem source. The intersection of these two sets produces a single set of corrective actions for a given problem source for an activity.

The purpose of suggesting corrective actions based on two sets of data (activity attributes and problem types) is to make use of supporting evidence from all sources as a form of corroborating information to suggest the most suitable corrective action(s). It is possible to suggest corrective actions based solely on reported problem sources. Accounting for the activity's attributes provides refinement of these suggestions. Accounting for the type(s) of problem(s) resulting also provides refinement. Taking both the attributes and the problem type(s) into account yields a set of corrective actions that are recommended more strongly if both sets of data point to them. Thus, the greater the amount of supporting evidence pointing to a corrective action, the more highly it is recommended.

For all problem sources, a possible corrective action may be simply to do nothing (the default). This is appropriate if the activity is near completion, if the problem is an isolated incident rather than a repetitive one, and/or if the activity does not repeat itself at other locations.

The building blocks used in the automated interpretation system are shown in Fig. 1. Field experience helped in the identification of activity attributes, problem sources, and corrective actions, as well as in the organization of this information in a hierarchical structure for automated interpretation. The block of expert rules draws upon information from the other building blocks in its selection of corrective actions. An application program guides the process, accessing an inference engine and the expert rule base, performing the calculations, processing the information, and presenting the output.

ACTIVITY REPRESENTATION

There has been an attempt to identify a generic set of attributes with which to describe an activity. This set is reasonably rich in scope, yet feasible

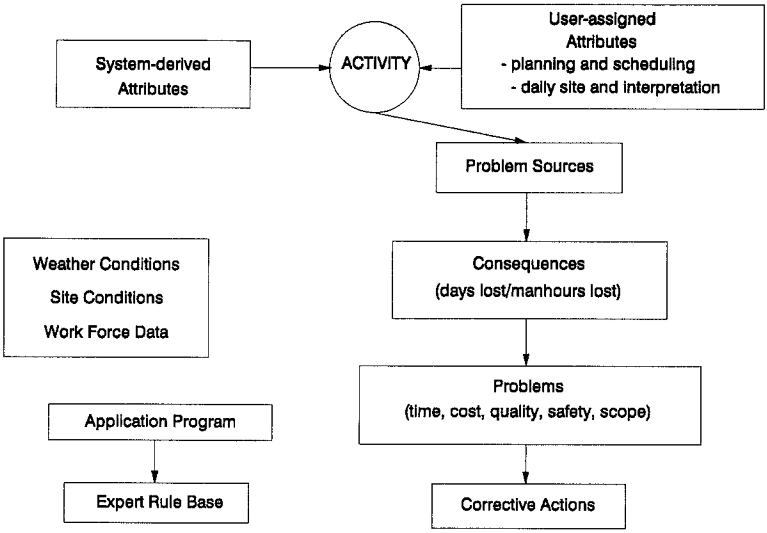

FIG. 1. Relationship between Data Elements Used in Automated Interpretation

in terms of the effort involved in determining attribute values. The assignment and derivation of attribute values allows the incorporation of individual activities into the reasoning processes directed at analyzing activity performance as a function of job conditions. Relevant corrective actions are suggested when appropriate. Other authors have also explored the issue of describing an activity. For example, Nay and Logcher (1985) use a frame representation with slot values to assign what they consider to be universal attributes for any work package. These include work-breakdown structure information, precedence relationships, resource requirements, and review data. They state, "Frame representation attempts to exploit situations in which knowledge fits stereotyped patterns and individual instances differ only in their details" [Nay and Logcher (1985), pages 129–130]. Hendrickson et al. (1987) use hierarchically organized frames with various slots to record information that defines activity attributes at various levels in the work-breakdown structure.

Activity attributes are described as user-assigned and system-derived. Planning and scheduling user-assigned attributes require the following data:

- Trade responsible for the activity
- Logic relationship(s) to other activities
- Duration of the activity
- Remaining duration of the activity as of the last progress date
- Percentage supplied (%S), and pecentage installed (%I) as of the last progress date
- Start or finish date constraints for the activity

For daily site reporting and automated interpretation purposes, user-assigned attributes are:

- Daily status (postponed, started, ongoing, idle, finished)
- Problem sources and a description of the circumstances

- Trade responsible for the problem source, if applicable
- Days and/or man-hours lost due to the problem source
- Activity interpretation attributes

System-derived attributes are calculated based on user-assigned attributes. They include:

- Early and late start and finish dates
- Critical or noncritical activity
- Amount of float an activity possesses
- Actual start and finish dates

The activity interpretation attribute set was developed as part of the schema for suggesting corrective actions. By assigning values from 0.0 to 1.0 (0.0 no effect, 1.0 significant effect), it is possible to distinguish one activity from another in terms of their relative sensitivity to various project conditions. The use of a numerical rating for each attribute per activity was selected instead of a linguistic variable (e.g. high, medium, low) because a rating avoids the need to specify membership functions for the fuzzy logic analysis schema devised. The issue of membership functions is further addressed in a subsequent section.

The attribute set identified to date is as follows:

- sensitivity to high precipitation
- sensitivity to low precipitation
- sensitivity to high temperature
- sensitivity to low temperature
- sensitivity to humidity
- sensitivity to wind
- sensitivity to ground conditions
- sensitivity to storage on site
- sensitivity to site congestion
- sensitivity to internal access
- sensitivity to external access
- how labor intensive
- how equipment intensive
- extent to which a buffer activity
- use of innovative methods
- subject to/requires design changes
- subject to/requires high inspection
- subject to/requires contract provision
- subject to/requires controlled environment
- subject to/requires low tolerance

Additional attributes may be appropriate (e.g. design complexity and susceptibility to learning curve effects).

PROBLEM SOURCES

A problem source is a condition that may affect one or more project performance measures—cost, time, safety, quality, or scope—thus creating a problem. A start has been made toward the development of a universal list of problem sources that can be recorded against activities. This list is intended to be comprehensive while maintaining an orthogonal relationship betwen problem sources. Orthogonality is both desirable and convenient for recording data in the field and for later analysis, since it implies that problem sources can be treated independently and do not affect each other. Therefore, corrective actions can be suggested for each problem source individually. Al-Tabtabai (1989) proposes cause-and-effect relationships among various problem sources, thus disputing their independence. Here, however, we treat them independently.

Below, grouped together in 10 categories, is a compilation of problem sources accumulated through an extensive literature search, field experience, and numerous brainstorming and discussion sessions with construction personnel. The list will undoubtedly benefit from further additions and modifications. A subset of these problem sources (indicated by an asterisk) was selected in order to develop and test a working system. The literature suggests that this subset represents the major recurring problems encountered in construction (Burati et al. 1992).

Environment

- Temperature too high
- Temperature too low
- Wind too high
- *Too much precipitation
- Too little precipitation
- Freeze-thaw cycles

Site Conditions

- Insufficient storage space
- *Inadequate external access
- Inadequate internal access
- Congestion
- Site not prepared/available
- *Poor ground conditions
- Change in/unexpected ground conditions
- Work space not cleaned

Owner and Consultants

- Decision(s) required
- Changes requested
- Interference or stop work orders
- Extra work requested
- Awaiting inspections/tests
- Excessive quality demanded

Design/Drawings

- Drawing errors
- Design changes/additions
- *Drawings insufficient/incomplete

- Conflicting information
- Poor design coordination

Schedule

- Delay of activity predecessor(s)
- Work done out of sequence
- Improper sequencing of activities
- Delay of off-site procurement

Workforce

- *Undermanning
- Overmanning
- Low skill level
- Excessive turnover
- Low motivation/morale
- Inadequate instructions
- Unsafe practices/accidents
- Fatigue (long shifts/overtime)
- Interference of other trades (trade stacking)
- Poor trade coordination

Work

- Estimating error
- Error in construction
- Layout error
- Poor workmanship
- Rework (design changes)
- *Rework (workmanship)
- Rework (work damaged by others)

Supplies and Equipment

- Insufficient materials
- Insufficient equipment
- Late delivery of materials
- Late delivery of equipment
- Tools/equipment breakdown
- Damaged deliveries
- Fabrication errors
- Inefficient materials handling

Utilities/City

- Awaiting permits
- Awaiting connection
- Awaiting inspections/tests
- Interference of existing utilities

- Damage of existing utilities
- *Unanticipated utilities

Miscellaneous

- Theft
- Strikes
- Vandalism
- Workers' Compensation Board shutdown
- Delay/change in award of contract
- Noise levels too high
- Natural disaster

CORRECTIVE ACTIONS

A hierarchy of corrective actions for problem sources in a generic construction project was developed and is found in Table 1. These actions do not necessarily correspond one-to-one with the problem sources identified in the previous section, but are intended to encompass all of them. [How best to organize this list is left for future investigation; the actions could be organized by problem type (time, cost, safety, quality, scope), or by problem source.] This list of corrective actions is by no means complete, but it does provide a framework for inserting more corrective action possibilities as they are identified.

For an example of the way in which problem sources are mapped onto corrective actions this scenario is presented. Activity XXYYZZ has a problem source "not enough man power" recorded against it and suffers from slow production due to the days lost from this problem source. Corrective actions will vary depending on the workforce data recorded for subtrade XX responsible for this activity. Possible corrective actions for this scenario are as follows:

1. If the manpower of subtrade XX is insufficient, then seek additional tradesmen and allocate them to activity XXYYZZ.
2. If the manpower of subtrade XX is sufficient, then reallocate manpower to activity XXYYZZ if it is critical or near critical, and if at least one other activity, preferably a buffer or noncritical activity, exists for which subtrade XX is responsible.

FUZZY ANALYSIS FRAMEWORK

Use of Fuzzy Set Theory

The uncertainty and imprecision involved in assessing problems related to construction activities has provided the impetus for the use of fuzzy sets. Furthermore, a method was required to represent mathematically the linguistic and numerical approximations used to describe the relationships among data items so that they can be manipulated by a computer—fuzzy set theory provides such a method. Fuzzy set theory and its applications are well explained in Schumucker (1984) (fuzzy sets and risk analysis), Ayyub and Haldar (1984) (project scheduling), Tong and Bonissone (1984) (generating linguistic solutions to fuzzy decision problems), Klir and Folger (1988) (fuzzy sets, uncertainty, and information), Smith and Hancher (1989) (estimating precipitation impacts for scheduling), Chang et al. (1990) (net-

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TABLE 1. Hierarchy of Corrective Actions

Corrective action category (1)	Action number (2)	Corrective action (3)
Do nothing (default)	0.0	
Environment	1.1	Provide a protected environment or shelter.
	1.2	Postpone activity to a time window with better anticipated weather conditions.
Work force	2.1	Seek additional tradesmen and allocate them to activity XXYYZZ.
	2.2	Reallocate man power from a buffer or noncritical activity XXSSTT to activity XXYYZZ.
	2.3	Weed out work force to upgrade skill level.
Construction methods	3.1	Conduct more on-site soil investigations.
	3.2	Use extra support or shoring to alleviate poor ground conditions.
	3.3	Use prefabricated elements.
	3.4	Use an alternate construction method.
	3.5	Use more equipment and less labor intensive construction methods.
Management	4.1	Postpone the activity.
	4.2	Do secondary work on the activity.
	4.3	Increase remaining duration of activity.
	4.4	Postpone interfering buffer or noncritical activities.
	4.5	Investigate sequencing of remaining work.
	4.6	Employ staggered shifts for interfering trades (trade stacking).
	4.7	Investigate use of shift work.
	4.8	Investigate use of scheduled overtime.
	4.9	Increase or improve supervision.
	4.10	Improve subtrade management/coordination.
	4.11	Employ a quality control program.
	4.12	Reallocate tools/equipment from a buffer or noncritical activity to a critical one.
	4.13	Purchase or rent backup equipment/tools.
	4.14	Establish improved equipment maintenance and management policies.
	4.15	Make periodic visits to fabricator's shop.
	4.16	Identify alternative supplier(s).
	4.17	Use alternative routes of access.
	4.18	Obtain street closure permit.
	4.19	Reschedule work to hours with less traffic.
	4.20	Obtain from the city a location map of all utilities on the site.
	4.21	Improve architect/engineer coordination.
	4.22	Monitor the activity but do nothing in the meantime.
Contract remedies	5.1	Pursue a project time extension for unreasonable delay due to weather (too much precipitation).
	5.2	Notify the Owner under a contract clause for unexpected conditions (ground conditions, utilities).
	5.3	Request a time extension from the Owner for unanticipated utilities.

TABLE 1. (*Continued*)

(1)	(2)	(3)
Protective actions	6.1	Issue memo to Owner requesting decision(s).
	6.2	Issue memo to party concerned to request drawing completion.
	6.3	Open a delay claim.
	6.4	Open an extra work order.
	6.5	Open a claim for acceleration.
	6.6	Open a back charge to a subtrade or supplier for delay.
	6.7	Open a back charge to a subtrade or supplier for extra work.
	6.8	Open a back charge to a subtrade or supplier for acceleration.
	6.9	Issue memo to supplier or fabricator requesting correction(s) for fabrication error(s).
	6.10	Notify the city of unanticipated utilities.
	6.11	Open a claim for conditions not covered by the contract.
Materials	7.1	Explore use of admixtures.

work resource allocation), Kouatli and Jones (1991) (designing fuzzy controllers), Grivas and Shen (1991) (pavement damage assessment), and Tee and Bowman (1991) (bridge condition assessment).

Assigning Activity-Interpretation Attributes

The user is required to assign interpretation attributes to each activity and give each attribute a weighting from 0.0 (no effect) to 1.0 (significant effect). The default is 0.0. These values are the "degree of applicability," D_{ai}, of attribute Va to activity i. For example, an excavation activity would most likely be highly sensitive (to degree 1.0) to high precipitation and to ground conditions, both of which would affect the progress of the work. It may be sensitive to degree 0.8 to site congestion and internal access if it makes use of large equipment. It may be labor intensive to degree 0.2 and equipment intensive to degree 1.0, indicating that it requires more equipment than labor. It may also be subject to a contract provision to degree 1.0 if unexpected ground conditions are encountered.

If we had adhered to the conventional approach of fuzzy logic with respect to an activity's attributes, a membership function would have to be defined for each attribute. Then, the user would respond to a query process to specify the applicability of attributes using linguistic values (e.g. high, medium, low). If this approach were adopted, one would have to ask whether the membership function is invariant across a broad spectrum of activity types (e.g. exterior versus interior work, labor intensive versus equipment intensive, and so forth). In construction, a diversity of activities exists, not a small set that is seen again and again. Thus, it is difficult to define membership functions that encompass all activities. Each activity, given its project context, could conceivably have its own membership function. Pursuit of this approach would involve enormous programming and specification tasks. Instead, for our approach, the user is required to assign a numerical value to each attribute for a given activity. Hence, the user has the freedom to use a different membership function for the same attribute in different activities. In assigning the numerical value, the user is aware of the activity at hand.

Fuzzy Analysis Schema A

In schema A (see Fig. 2), a set of corrective actions for a problem source can be selected based on the activity's attributes. A three-step approach is involved. First, the user defines a standard relationship set between the problem source and activity-interpretation attribute set, independent of any activity. Second, an activity-specific relationship set linking problem sources with interpretation attributes is determined by multiplying the standard set by the activity-interpretation attribute vector *Dai*, discussed previously, for all *i*. Third, activity interpretation attributes are mapped onto corrective actions using expert system rules.

Problem sources are mapped onto the set of interpretation attributes, independent of any activity, by asking the question, "If an activity possesses this attribute with a strength of 1.0, how strongly would this affect the choice of corrective action(s) given the presence of this problem source?" The answer to this question yields a number ranging from 0.0 (no effect) to 1.0 (significant effect). Another way to view this mapping is to ask the question, "Given that an activity possesses this attribute at full strength (1.0), to what degree (from 0.0 to 1.0) would the activity be sensitive to this problem source?"

The linkage between a problem source, *Xj*, and a user-assigned interpretation attribute, *Va*, is called the *standard strength* (*Bja*). For example, if the problem source is "drawings insufficient/incomplete," then the activity attribute "subject to design changes" would be likely to affect the choice of corrective action to degree 1.0 (significant effect); or, given that an activity is "subject to design changes," the problem source "drawings insufficient/

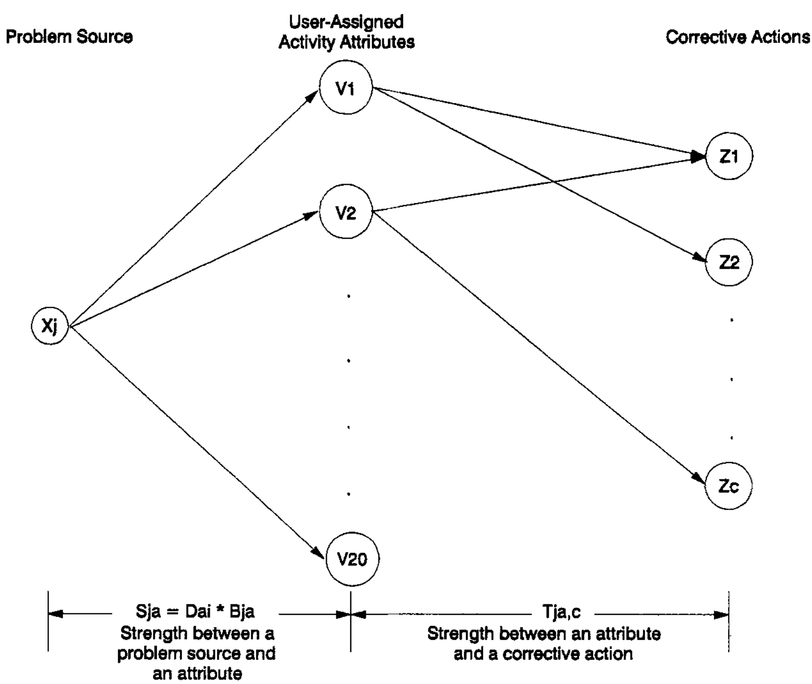

FIG. 2. Analysis Schema A

incomplete" is highly likely (to degree 1.0) to occur. In turn, this attribute would point to a corrective action for this problem source that would improve procedures for assigning priorities to drawing production and/or drawing control.

In the second step, for a given activity *i* under analysis, the strength of the linkage, represented by *Sja*, between a problem source *Xj* and a user-assigned interpretation attribute *Va*, is calculated by multiplying the "degree of applicability," *Dai*, of *Va* by the "standard strength," *Bja*. This calculation is performed in the application program. For example, if activity XXYYZZ is high precipitation sensitive to degree 0.8 (*Dai*), and the problem source "poor ground conditions" is related to high precipitation sensitivity to degree 0.5 (*Bja*), then for this activity the problem source "poor ground conditions" is related to the interpretation attribute "high precipitation sensitivity" to degree 0.4 (*Sja*) (i.e. $0.8 \times 0.5 = 0.4$).

To complete the three-step approach, interpretation attributes are mapped onto corrective actions for a given problem source, with strengths ranging from 0.0 (do not do this corrective action) to 1.0 (this corrective action is recommended 100%). This strength is represented by *Tja, c* (problem source *Xj*, interpretation attribute *Va*, corrective action *Zc*). These strengths are influenced by

- Activity attributes, such as the degree of criticality of the activity, and the trade responsible for the activity
- Weather and site conditions
- Workforce data
- The remaining duration of the activity

Thus, unlike the problem-source/activity attribute linkage process, we do not start with a standard mapping and then tailor it for the activity at hand. Instead, we use the foregoing data to derive predicate values for use in a set of expert rules to determine the strength with which a given corrective action applies. These rules are accessed by the application program. For example, for the problem source "too much precipitation" and an activity that is "high precipitation sensitive," a corrective action of "provide a protected environment or shelter" is suggested with a strength of:

- 1.0, if the activity is critical; if the precipitation on site is greater than or equal to 12 mm on any day in the time window under analysis; and if the remaining duration of the activity is greater than or equal to 50% of the scheduled duration, and greater than or equal to three days
- 0.8, if the activity is noncritical; if the precipitation on site is greater than or equal to 12 mm on any day in the time window under analysis; and if the remaining duration of the activity is greater than or equal to 50% of the scheduled duration, and greater than or equal to three days
- 0.4, if the activity is critical; if the precipitation on site is less than 12 mm for each day in the time window under analysis; and if the remaining duration of the activity is greater than or equal to 50% of the scheduled duration and greater than or equal to three days
- 0.0, otherwise

In formulating such rules, consideration must be given to defining what constitutes severe operating conditions (e.g. a threshold of 12 mm of rain), the time required to initiate corrective action, and so forth.

Fuzzy Analysis Schema B

Corrective actions can also be selected based on the type of problem arising out of a problem source. This analysis schema (schema B) is represented in Fig. 3. Problem sources are mapped onto the types of problems with a strength *Pjd*, based on the attributes of the problem source, such as days or man-hours lost, or based on the type of problem source. (Note that under schema A, no consideration is given to man-hours or time lost. This is intentional, since in practice, field personnel may flag a problem source as present but not provide an estimate of man-hours or time lost, even if they occur, because at the time the problem arose it was not possible to provide an estimate. Consequently, we do not wish to ignore problem sources that have no apparent time or cost implications. Schema B assumes that no problem exists in the absence of time and cost impacts. If time and cost impacts are not recorded in the field, they may be assessed at a later date by an office adjustment and therefore taken into account in the data interpretation under schema B.) For purposes of this study, only the problem source of "rework due to workmanship" points to a quality problem. The other possible problems are time, cost, and no problem. (As stated previously, the problems of safety and scope have yet to be addressed.) The type of problem arising from a problem source is determined by the application program according to the rules found in Fig. 4.

For a given problem source, problem types are mapped onto corrective

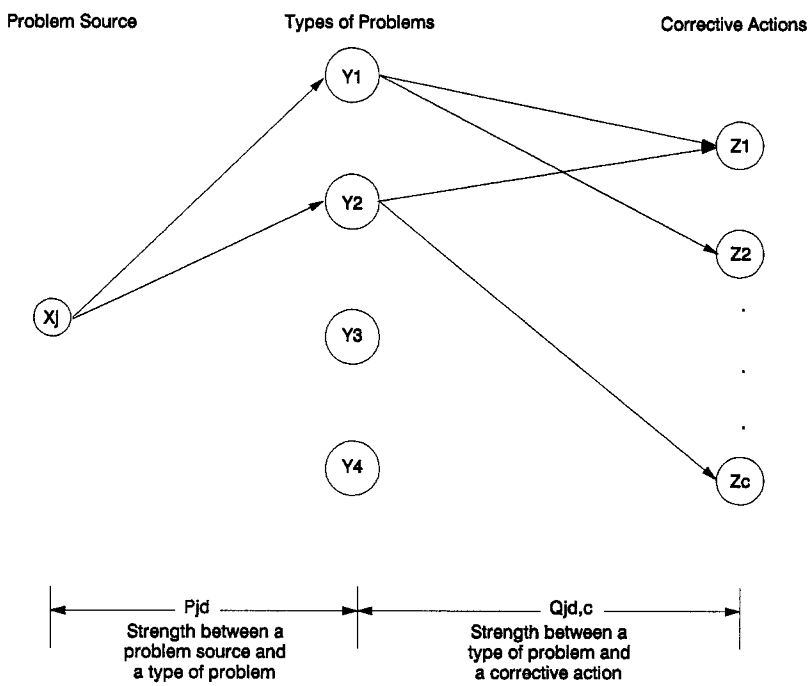

FIG. 3. Analysis Schema B

The four types of problems are:
(1) time
(2) cost
(3) quality
(4) no problem,
They are represented by the set Y.
Problem source Xj points to problem Yd with a strength Pjd ranging from 0.0 to 1.0, where j represents the problem source and d the problem type.
Pjd is determined from the system-derived variables as follows:

(1) DO THIS FIRST = DEFAULT
If the total number of days lost from all problem sources is >= total float (as of current progress date), then:
Pj1 = 1.0
Pj2 = 0.0
Pj4 = 0.0.

(2) IN ALL CASES
If the problem source (Xj) is rework (workmanship), then:
Pj3 = 1.0.
Otherwise,
Pj3 = 0.0.

(3) The 'degree of non-criticality' = # of days of total float/remaining duration.
The 'criticality index' = 1.0 - 4(degree of non-criticality),
where 0.0 <= criticality index <= 1.0.
If the total float is negative, then 'criticality index' > 1.0; therefore, set the 'criticality index' to 1.0.

(4) For a given activity i and a given problem source Xj:
(a) If there are days lost only (no manhours lost), then
Pj1 = max[default, criticality index]
Pj2 = 0.0
Pj4 = 0.0.

(b) If there are manhours lost only (no days lost), then
Pj1 = 0.0
Pj2 = 1.0
Pj4 = 0.0.

(c) If there are both days lost and manhours lost, then
Pj1 = max[default, criticality index]
Pj2 = 1.0 - criticality index
Pj4 = 0.0.

(d) If there are no manhours lost, no days lost, and the problem source is not rework (workmanship), then
Pj1 = Pj2 = Pj3 = 0.0
Pj4 = 1.0.

FIG. 4. Rules to Determine Type of Problem (*Yd*) Arising out of Problem Source (*Xj*)

actions, which have strengths ranging from 0.0 to 1.0. The strength of this mapping is influenced by the frequency of the problem source in the time window under analysis, since multiple occurrences of a problem source warrant more attention than a single occurrence. The following function was selected to relate the strength of the weighting to the frequency of the problem source:

$$W = \sin\hat{}2\left(pi \cdot \frac{f}{2}\right); \quad 0.0 \le f \le 1.0; \quad 0.0 \le W \le 1.0 \quad \ldots \ldots \ldots \ldots (1)$$

where f = frequency of problem source, which is computed by the number of days of occurrence of that problem source divided by the number of days in the time window under analysis, when activity status is recorded for that activity; and W = a factor used in determining the weighting between a problem type (Yd) and a corrective action (Zc); W is calculated by the application program and is multiplied by a factor that is context-dependent and forms part of the relevant expert rule, which calculates the strength of the weighting between a problem type (Yd) and a corrective action (Zc). This strength is known as Qjd, c. For example, for the problem source "too much precipitation" and the problem "time," the corrective action "provide a protected environment or shelter" is linked to the problem "time" with a strength of $Qjd, c = 1.0 \cdot W$.

Once a specific threshold frequency is reached (0.5 in our case) W should increase quickly and reach almost full weighting for a large part of the range beyond the threshold frequency. This signifies that frequency values beyond the threshold are of similar severity, hence a recurring problem source. For example, a problem source that occurs with a frequency of 0.9 is virtually as significant as one that has a frequency of 1.0, and both should be given a strong weighting around 1.0. Any other function that would have satisfied the aforementioned criteria could be readily substituted. This particular one was chosen for its simplicity and convenience.

Fuzzy Binary Relations

A relationship is required to link two sets of data directly to each other through their respective relationships to a third and common set. The fuzzy binary relation approximates the relationship between two data items without having to resort to fuzzy membership sets, which we have sought to avoid for the reasons described previously.

Each mapping between two sets of data is a fuzzy binary relation that can be represented as a matrix. The elements of the matrix represent the fuzzy degrees of membership of each link. We denote the relationship between the problem source set X, and activity interpretation attribute set V by the matrix $S(X, V)$. Each activity has its own matrix. Each element of this matrix corresponds to the strength of the linkage between problem source Xj and interpretation attribute Va, for a given activity, and is represented by $S(Xj, Va)$. This corresponds to the value Sja, described in analysis schema A. Note that $S(X, V)$ corresponds to the matrix of standard strengths linking problem sources with activity attributes discounted by the degree of applicability that the attribute has for the activity at hand. Similarly, the relationship between the interpretation attribute set V and the corrective action set Z is represented by the matrix $T(V, Z)$. Each element of this matrix, derived through the use of a set of expert rules, represents the strength of the linkage between interpretation attribute Va, and a corrective action Zc, and is represented by $T(Va, Zc)$. This corresponds to the value Tja, c, described in analysis schema A.

A composition operation was employed to link two data sets through their respective relationship to a third and common set. This operation, performed on $S(X, V)$ and $T(V, Z)$, is used to determine the relationship between problem sources X, and corrective actions Z, through their respective relationship to interpretation attributes, V. The composition of these two relations is denoted by

$$R1(X, Z) = S(X, V) \circ T(V, Z) \quad \text{(2)}$$

The elements of $R1$ correspond to the strengths of the linkages among problem sources and corrective actions, and will always lie between 0.0 and 1.0.

One common composition operation for fuzzy relations is the maximum-minimum (max-min) composition, as outlined in Klir and Folger (1988). This operation is defined, for a given Xj and Zc, by

$$S \circ T(Xj, Zc) = \max \min[S(Xj, Va), T(Va, Zc)] \quad \text{for all } Va \ldots\ldots. (3)$$

where $S \circ T(Xj, Zc)$ defines the membership function for the elements Xj and Zc of the matrix $R1(X, Z)$. The max-min composition for fuzzy relations is performed in our system by the application program and indicates the strength of a relational chain between elements of X and Z. "This strength is represented by the membership grade of the pair (x, z) in the composition. The strength of each chain equals the strength of its weakest link and the strength of the relation between elements x and z is then the strength of the strongest chain between them" [Klir and Folger (1988), page 75]. This composition is used to determine the most likely corrective action based on the strongest indicator, since corrective actions are suggested with a strength equaling that of the strongest chain between them.

The same logic can be applied in linking problem sources to corrective actions, taking into account the type of problem caused by a problem source (schema B). Problem sources point to one or more problems with different strengths, in accordance with the set of rules outlined in Fig. 4. In turn, problems point to various corrective actions, again with different strengths. The most appropriate corrective action depends on the type of problem that needs the greatest attention and on the frequency of occurrence of the problem source. The fuzzy binary relationships between problem sources and problems, and between problems and corrective actions are represented, respectively, by $P(X, Y)$ and $Q(Y, Z)$, where Y represents problems. Thus, the fuzzy max-min composition for schema B is represented by

$$R2(X, Z) = P(X, Y) \circ Q(Y, Z) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

The membership function of $R2(X, Z)$ is defined, for a given Xj and Zc, by

$$P \circ Q(Xj, Zc) = \max \min[P(Xj, Yd), Q(Yd, Zc)] \quad \text{for all } Yd \ldots\ldots (5)$$

An alternative composition operation is the cumulative-minimum (cum-min) composition. For schema A this operation is defined, for a given Xj and Zc, by

$$S \circ T(Xj, Zc) = \text{cum} \min[S(Xj, Va), T(Va, Zc)] \quad \text{for all } Va \ldots\ldots. (6)$$

to yield elements of the matrix $R1(X, Z)$. Similarly, for analysis schema B, $R2(X, Z)$ is defined, for a given Xj and Zc, by

$$P \circ Q(Xj, Zc) = \text{cum} \min[P(Xj, Yd), Q(Yd, Zc)] \quad \text{for all } Yd \ldots\ldots (7)$$

The cum-min composition for fuzzy relations is performed by the application program and indicates the strength of a relational chain between elements of X and Z. The strength of each chain between any two elements of X and Z equals the strength of its weakest link, and the strength of the relation between the two elements equals the summation of the strength of all chains between them. The reasoning behind this rule is that each pointer to a corrective action increases the strength with which it is recommended.

Various items of information can suggest that a corrective action is suitable. The more supporting evidence that exists, the more highly a corrective action is recommended.

Given the two fuzzy binary relations $R1(X, Z)$ and $R2(X, Z)$ to describe the relationship between problem sources, X, and corrective actions, Z, a fuzzy binary relation $R(X, Z)$, which combines the two relations, was required. It is represented, for a given Xj and Zc, by

$$R(X, Z) = R1(X, Z) \text{ intersection } R2(X, Z) \quad (8)$$

$$R(Xj, Zc) = \min[R1(Xj, Zc), R2(Xj, Zc)] \quad (9)$$

The intersection operation was chosen since it assigns the minimum of two strengths as the strength with which a corrective action is suggested, thus erring on the conservative side.

The most likely corrective action for an activity is the corrective action with the strongest membership in the $R(X, Z)$ matrix. The maximum strength with which a corrective action is suggested is 100%, even if it has a membership in $R(X, Z)$ greater than 1.0, which may occur using the cum-min composition. (For this case, one approach might be to normalize the strengths based on the highest strength in excess of 1.0. This has not been done.) Corrective actions can also be ranked in terms of benefit to the activity, based on their degree of membership in the $R(X, Z)$ matrix. This latter approach is used in our system. Since there is a certain degree of imprecision and subjectivity in the information collected on-site and used in the automated interpretation, it is left to the user to select the most suitable corrective action(s) based on the rankings provided by the automated analysis, hence the system is assigned the role of assistant.

EXAMPLE

The problem source "too much precipitation" ($X1$) has been recorded against an activity that possesses the following user-assigned interpretation attributes and degrees of applicability (Dai) shown in Table 2.

The elements of the standard strength matrix (Bja) with which problem source $X1$ points to each of these attributes are

$$\begin{array}{cc} & \begin{array}{ccc} V1 & V7 & V12 \end{array} \\ X1 & \begin{bmatrix} 0.6 & 0.4 & 1.0 \end{bmatrix} \end{array}$$

Then, the elements of the matrix $S(X, V)$ are computed as $Dai \cdot Bja$, which follows:

$$S(X1, V1) = 1.0 \cdot 0.6 = 0.6 \quad (10)$$

$$S(X1, V7) = 0.5 \cdot 0.4 = 0.2 \quad (11)$$

$$S(X1, V12) = 0.3 \cdot 1.0 = 0.3 \quad (12)$$

TABLE 2. Example Activity Attributes and Sensitivities

Attribute (1)	Attribute description (2)	Dai (3)
$V1$	Sensitive to high precipitation	1.0
$V7$	Sensitive to ground conditions	0.5
$V12$	Labor intensive	0.3

$S(X, V)$ is then

$$\begin{array}{cc} & \begin{array}{ccc} V1 & V7 & V12 \end{array} \\ X1 & \left[\begin{array}{ccc} 0.6 & 0.2 & 0.3 \end{array}\right] \end{array}$$

Assume that, using the expert rules described previously, and the corrective action set of Table 1, matrix $T(V, Z)$ is

$V\backslash Z$	1.1	1.2	3.2	4.3	4.22	4.23	5.1
$V1$	1.0	0.0	0.0	0.0	0.2	0.0	1.0
$V7$	0.5	0.0	1.0	0.0	0.2	0.0	1.0
$V12$	0.4	0.0	0.0	0.0	0.0	0.0	0.0

Using the max-min composition

$$R1(X1, Z1.1) = \max[\min(0.6, 1.0), \min(0.2, 0.5), \min(0.3, 0.4)] \quad (13a)$$

$$R1(X1, Z1.1) = \max[0.6, 0.2, 0.3] \quad (13b)$$

$$R1(X1, Z1.1) = 0.6 \quad (13c)$$

The resulting $R1(X, Z)$ matrix is

$X\backslash Z$	1.1	1.2	3.2	4.3	4.22	4.23	5.1
$X1$	0.6	0.0	0.2	0.0	0.2	0.0	0.6

Using the cum-min composition

$$R1(X1, Z1.1) = \text{cum}[\min(0.6, 1.0), \min(0.2, 0.5), \min(0.3, 0.4)] \quad (14a)$$

$$R1(X1, Z1.1) = \text{cum}[0.6, 0.2, 0.3] \quad (14b)$$

$$R1(X1, Z1.1) = 1.1 \quad (14c)$$

The resulting $R1(X, Z)$ matrix is

$X\backslash Z$	1.1	1.2	3.2	4.3	4.22	4.23	5.1
$X1$	1.1	0.0	0.2	0.0	0.4	0.0	0.8

Thus, as noted previously for the cum-min composition rule, a strength in excess of 1.0 can be achieved.

Continuing the same example, assume that both a time ($Y1$) and cost ($Y2$) problem result, with respective strengths of 0.6 and 0.4, as determined by the rules in Fig. 4; thus

$$P(X1, Y1) = 0.6 \quad (15a)$$

$$P(X1, Y2) = 0.4 \quad (15b)$$

$P(X, Y)$ is then:

$$\begin{array}{cc} & \begin{array}{cc} Y1 & Y2 \end{array} \\ X1 & \left[\begin{array}{cc} 0.6 & 0.4 \end{array}\right] \end{array}$$

Using an assumed frequency of the problem source and the accompanying expert rules described previously, matrix $Q(Y, Z)$ is

$Y\backslash Z$	1.1	1.2	3.2	4.3	4.22	4.23	5.1
$Y1$	1.0	0.6	1.0	1.0	0.0	0.0	1.0
$Y2$	0.5	1.0	1.0	1.0	0.0	0.0	0.0

Using the max-min composition

$$R2(X1, Z1.1) = \max[\min(0.6, 1.0), \min(0.4, 0.5)] \quad (16a)$$

$$R2(X1, Z1.1) = \max[0.6, 0.4] \quad (16b)$$

$$R2(X1, Z1.1) = 0.6 \quad (16c)$$

The resulting $R2(X, Z)$ matrix is

$X\backslash Z$	1.1	1.2	3.2	4.3	4.22	4.23	5.1
$X1$	0.6	0.6	0.6	0.6	0.0	0.0	0.6

Using the cum-min composition

$$R2(X1, Z1.1) = \mathrm{cum}[\min(0.6, 1.0), \min(0.4, 0.5)] \quad (17a)$$

$$R2(X1, Z1.1) = \mathrm{cum}[0.6, 0.4] \quad (17b)$$

$$R2(X1, Z1.1) = 1.0 \quad (17c)$$

The resulting $R2(X, Z)$ matrix is

$X\backslash Z$	1.1	1.2	3.2	4.3	4.22	4.23	5.1
$X1$	1.0	1.0	1.0	1.0	0.0	0.0	0.6

Recapping the example employing the max-min composition

$X\backslash Z$	1.1	1.2	3.2	4.3	4.22	4.23	5.1
$R1(X1, Z)$	0.6	0.0	0.2	0.0	0.2	0.0	0.6
$R2(X1, Z)$	0.6	0.6	0.6	0.6	0.0	0.0	0.6

Thus, $R(X1, Z) = R1(X1, Z)$ intersection $R2(X1, Z)$ is

	1.1	1.2	3.2	4.3	4.22	4.23	5.1
$X1$	0.6	0.0	0.2	0.0	0.0	0.0	0.6

Corrective actions 1.1 and 5.1 would be suggested with a strength of 60%, and corrective action 3.2 would be suggested with a strength of 20%.

Using the cum-min composition

$X\backslash Z$	1.1	1.2	3.2	4.3	4.22	4.23	5.1
$R1(X1, Z)$	1.1	0.0	0.2	0.0	0.4	0.0	0.8
$R2(X1, Z)$	1.0	1.0	1.0	1.0	0.0	0.0	0.6

Thus, $R(X, Z) = R1(X, Z)$ intersection $R2(X, Z)$ is

	1.1	1.2	3.2	4.3	4.22	4.23	5.1
$X1$	1.0	0.0	0.2	0.0	0.0	0.0	0.6

Thus, for the cum-min composition rule, corrective action 1.1 would be 100% recommended; 5.1, 60% recommended; and 3.2, 20% recommended.

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EXTENSIONS TO AUTOMATED ANALYSIS

The present system performs the automated interpretation on an activity-by-activity basis. It also suggests corrective actions for a given activity considering each problem source individually. Given a current system potential of 90 problem sources, and considering a project with several hundred activities, the number of corrective actions that could potentially be suggested is massive. To cope with this, a future extension needs to integrate over all problem sources for a given activity to produce one set of corrective actions. Other extensions left for future investigation are concerned with rolling up the activity-by-activity analysis to the responsibility (subtrade) level, and further to the project level, with the aim of detecting a repetitive theme or pattern of corrective actions for which a higher level of corrective actions might be appropriate (e.g. terminate a contract, change a supplier, change management personnel, etc.). Also, a feedback loop should be incorporated into the activity analysis schema to account for corrective actions initiated due to prior analysis. Other reasoning schema, which would link activity attributes, problem sources, and site conditions with corrective actions, should also be explored.

CONCLUSION

A framework was developed for an automated interpretation of job records which will identify problem activities and suggest corrective actions. Building blocks of this framework include a set of user-assigned activity attributes, a set of problem sources, a set of corrective actions, and expert rules. Fuzzy logic is introduced in an attempt to represent the human reasoning process. Implementation of this framework in the form of a prototype system has been done, and will be described in a companion paper. Validation of the prototype on an actual construction project is the next step, and is in progress.

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