AN OBJECT-ORIENTED APPROACH FOR SCHEDULING OF CONSTRUCTION PROJECTS

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ABSTRACT

Robotic construction equipment will need to plan and replan in response to rapidly changing site and external market conditions of a project. A group of researchers at Stanford University is conducting research on the potential of artificial intelligence (AI) techniques to develop enhanced tools for generating plans and schedules automatically from CAD descriptions of facilities. Currently available network-based project scheduling tools provide capabilities for heuristic resource leveling and resource-constrained scheduling; however they are only of limited value in making time-cost tradeoff decisions when project completion times must be shortened. To address this limitation, the authors are developing JANUS, a knowledge-based system for simulating and analyzing time-cost tradeoff issues on facility projects in more detail. This paper lays out the rationale underlying the design of JANUS, and describes the architecture of a prototype system developed using IntelliCorp's KEE™ knowledge processing environment.

INTRODUCTION

Purpose of the research

The work described in this paper grew out of research into the automatic generation of schedules from project descriptions, specifically from CAD representations of project elements. Related work focuses on interpreting CAD drawings, developing lists of activities and determining salient relationships among those activities. This work focuses on extending this body of research into the realm of schedule analysis and resource allocation among activities.

The primary objectives of this research are: 1) to model the process of time-cost tradeoff analysis and 2) to demonstrate the dependence of this analysis on the varying goals of the project participants. The notion of trading money for time is an intuitively appealing one which has been evaluated historically a number of ways. Traditional linear programming approaches suffer from the drawbacks of requiring a great deal of data, which is often difficult to obtain, and of requiring a great deal of computation. Simpler methods of approximation utilize simplistic activity cost curves yet still require a great deal of data up front to enable the analysis. Our solution is to use AI programming techniques to allow analysis of time-cost tradeoffs with less initial data, but based on realistic expediting tactics and allowing for varying goals of the project participants.

Scope of the paper

This paper will present the conceptual architecture for JANUS, a knowledge-based time-cost tradeoff simulator. (All knowledge-based systems need a catchy name. Janus is the Greek *Doorkeeper of Heaven and Patron of the Beginning and End of Things*… appropriate, we think. It may also mean 'Just Another Nascent Utility for Scheduling.')

First, we discuss the current state of the art for time-cost tradeoff analysis. Then we describe the architecture of the JANUS system and some of the details of its implementation. A related paper will present the organizational and management-related aspects of the model in more detail [Axworthy 89].

Review of the literature

Traditional network-based project scheduling tools provide capabilities for heuristic resource leveling and resource-constrained scheduling [Fondahl 64]. Procedures exist to analyze time-cost tradeoff decisions [Moder 83] but they do not account for the varying perceptions of the value of time to the project participants.

[Cherneff 88] and [Hendrickson 87b] both describe systems to generate a construction plan automatically from a description of building components. Both systems currently utilize single estimates of activity durations based upon quantity take-offs and production estimates. Neither makes any attempt at a time-cost tradeoff analysis. [Hendrickson 87a] describes a system to estimate single activity durations in the domain of masonry construction. It develops activity durations based on quantities of work, prevailing weather conditions, numbers of crews and estimates of expected productivity, but includes no notion of time-cost tradeoff. [Levitt 85] describes a system which utilizes user-supplied optimistic and pessimistic estimates of activity duration along with actual durations observed to date to forecast expected durations for remaining work. This system attempts to predict future behavior based on experience, but makes no attempt to evaluate time-cost relationships among activities in a network. [Logcher 88] extends Levitt's & Kunz's views of activities as self-aware entities or "objects" and suggests object-oriented programming as a reasonable paradigm for scheduling.

[Barber 88] describes an implementation of Siemens' algorithm for time-cost tradeoff analysis. This algorithm utilizes six constraints on an activity to determine an effective cost for that activity. These constraints are 1) the feasibility of expediting the activity; 2) the cost of expediting the activity; 3) the effect on available resources of expediting the activity; 4) the desirability of continuing to expedite one activity rather than jump to another; 5) the number of paths that share the activity; 6) how early the activity occurs in the network. Activities are selected for expediting based on their 'effective cost,' a heuristic value derived from evaluating these six constraints. This work describes an abstraction hierarchy for expediting tactics but does not deal with the varying goals of the project participants.

[Koo 87] discusses the problems of coordinating communications and decisions among intelligent autonomous agents. Autonomous robots on construction sites will require analysis of the type described in this paper in order to plan their work effectively.

THE JANUS SYSTEM

Overview of the system

The JANUS system is an attempt to tackle the time-cost tradeoff in a manner that captures the motivational as well as the technical aspects of trading direct cost for time savings. JANUS uses activity sequence, time and cost relationships and a set of generic expediting tactics for its time-cost tradeoff analysis. It also represents project participants and derives their goals from the client's view of the project and the contractual provisions under which each project participant is employed. Each activity has a responsible participant who determines the value of time and therefore the maximum amount that may be spent expediting the activity. It can thus provide a more meaningful forecast of the results of alternative strategies – contractual as well as technical – to shorten project duration.

JANUS will perform the following tasks:

- it will calculate traditional critical path method (CPM) data,
- it will determine activity durations, considering manhour estimates, activity crew preference, alternate crews, feasible expediting tactics and activity ownership.

The research focuses on two primary functions: 1) determining the value of time (in terms of dollars per day) for the various project participants and 2) matching expediting tactics with critical activities to shorten the overall project duration. To implement these functions, we use hierarchical frame descriptions of the participants, their contracts, the project, its activities and available resources along with production rules to control the analysis.

Representation

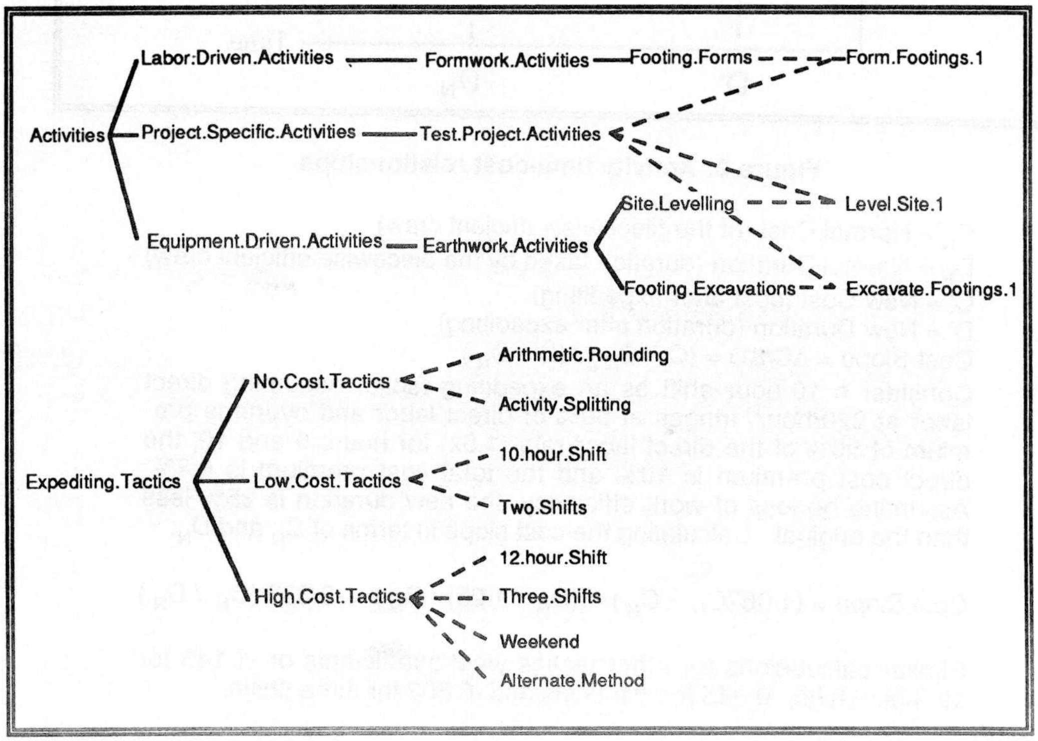

Figure 1: Examples of frame hierarchies

Hierarchical frame representations of project activities and expediting tactics are depicted. Subclass relationships are indicated by solid lines, instance relationships by dashed lines. These hierarchies are incomplete but include some useful concepts. Note the multiple inheritance of all instance activities receiving project specific data from Project.Specific.Activities and other data from their generic activity parents.

involve a base rate of straight time, supplemented by some amount of overtime or shift premium. The second difference is in the efficiency of the tactic. Studies have shown [BRT 80] that working a small amount of overtime periodically has a negligible effect on productivity but regularly-scheduled overtime and multiple shifts have significant impacts. We have arbitrarily selected a cost slope of 50% of an activity's normal cost per day as the dividing line between low cost and high cost tactics. See Figure 3 for a sample calculation.

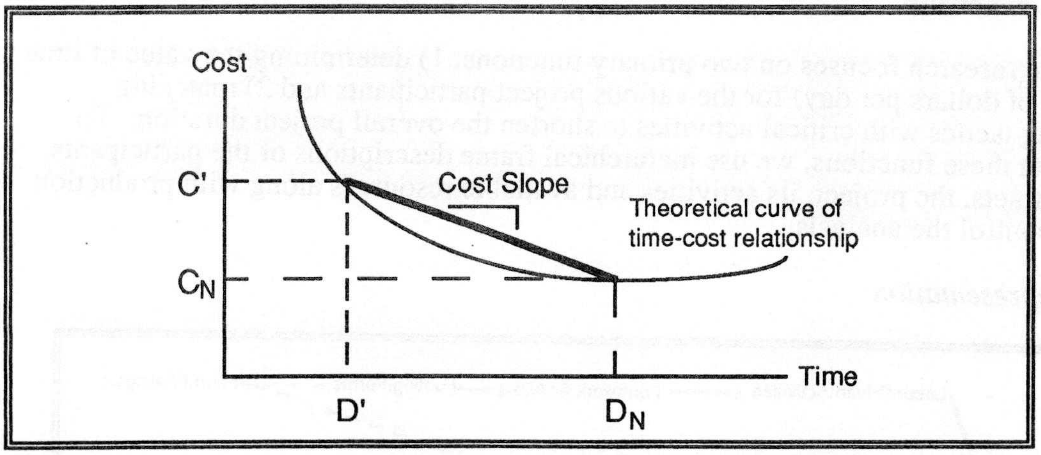

Figure 3: Activity time-cost relationships

C_N = Normal Cost (of the piecewise efficient crew)
D_N = Normal Duration (duration taken by the piecewise efficient crew)
C' = New Cost (cost after expediting)
D' = New Duration (duration after expediting)
Cost Slope = $\Delta C/\Delta D = (C' - C_N) / (D' - D_N)$

Consider a 10-hour shift as an expediting tactic. Assuming direct labor at $20/hour, fringes at 50% of direct labor and overtime premium of 50% of the direct labor rate (1.5x) for hours 9 and 10, the direct cost premium is 10% and the total cost premium is 6.7%. Assuming no loss of work efficiency, the new duration is 25% less than the original. Calculating the cost slope in terms of C_N and D_N:

$$\text{Cost Slope} = (1.067C_N - C_N) / ((D_N / 1.25) - D_N) = -0.333 (C_N / D_N)$$

Similar calculations for other tactics yield coefficients of -1.143 for 12–hour shifts, -0.345 for two shifts and -0.803 for three shifts.

Reasoning

The factors affecting a participant's perceived value of time include its daily indirect costs, its capital structure, its contractual relations with other participants and its continuing relations with other participants. We simplify this analysis by the following assumptions:

- the owner's time value is entered by the user;
- if the prime contract is cost-plus, the contractor's time value is that of the owner;
- if the prime contract is lump sum, the contractor's time value is that of the bonus/penalty clause if there is one, otherwise it is its daily indirect rate;
- subcontractors' time values are their daily indirect rates.

Our model represents contracts, participants, activities, crews & expediting tactics as frames. Figure 1 shows portions of the frame hierarchies for activities and expediting tactics. Slots within the frames define object behavior and relationships. For example, a cost-plus contractual relationship between participants causes the employed participant to value time at the same rate as its employer. Behavior includes calculation of traditional CPM data as well as reasoning about and calculation of activity duration, based on the current state of the overall network, the current expedited state of the activity, the type of activity it is and the expediting strategies available to it. We support the assertion of [Logcher 88] that object-oriented programming is a useful method of implementing project management support tools.

The representation of expediting tactics is particularly interesting. Tactics in our context relate to specific ways of shortening the activity durations. Figure 2 shows an example of a frame representing a specific expediting tactic. We categorize tactics in three groups: no cost tactics, low cost tactics and high cost tactics. No cost tactics involve network manipulations, including arithmetic rounding and activity splitting. Our system employs a 'most conservative' initial approach to the schedule: the first time through, durations are rounded up to allow as much slack as possible. If the project goals do not support such slack, then the durations must be rounded down. By splitting, we mean to allow some activities, those where such splitting is feasible, to be split into 2 or 3 separate steps. This splitting allows decoupling non-critical preparation and/or cleanup work from the production portion of the activity, allowing some reduction of the critical path. The application of these tactics is really independent of any other considerations and is performed on each critical activity before any other tactics are considered.

10.Hour.Shift		
Calculate.Coefficient	method	(from Expediting.Tactics)
Calculate.Duration.Reduction	method	(from Expediting.Tactics)
Calculate.Premium	method	(from Expediting.Tactics)
Crew.Hours.per.Day	10	(from 10.Hour.Shift)
Cost.Premium.Percent	0.067	(calculated locally)
Cost.Slope.Coefficient	-0.333	(calculated locally)
Duration.Reduction.Percent	0.25	(calculated locally)
Effective.Hours.per.Day	10.0	(calculated locally)
Efficiency	1.0	(from 10.Hour.Shift)

Figure 2: One of the "Expediting.Tactics" frames with its slots

This figure shows some of the slots in the frame 10.hour.Shift, which is a member of the class Expediting.Tactics. Note the data-holding slots Crew.Hours.per.Day, Cost.Slope.Coefficient, Efficiency, etc. and the method or procedure-holding slots Calculate.Coefficient, etc. Calculate.Coefficient is inherited from the root class, Expediting.Tactics, Cost.Slope.Coefficient is calculated by one of the inherited methods and Efficiency is defined locally.

Low cost and high cost tactics differ from each other in two ways. First is the basic hourly cost necessary for each tactic. High cost tactics typically involve many hours of high premium work, i.e., time-and-a-half or double-time. Low cost tactics typically

The time-cost tradeoff analysis utilizes a 'favorite crew' for each activity. This crew represents the most efficient means of performing that activity. If this piecewise efficient collection of activities and crews satisfies project goals, then the analysis need not continue. If not, activities must be selected for expediting, means of duration reduction must be selected and new durations and costs must be calculated. The results are then checked against the project goals. Analysis continues until either the goals are satisfied or no critical activities can be expedited for less cost than their responsible participant puts on the value of time.

Activities are selected for expediting based on their criticality and their location in the network, with priority given to early activities and to those constraining many others. Expediting tactic selection is dependent on the state of the analysis and on the amount of schedule reduction still required. In general, no cost tactics are employed first, low cost tactics if no cost tactics provide insufficient schedule reduction and high cost tactics only when all else fails to achieve project goals. An activity is not expedited if the cost of further reduction exceeds its responsible participant's perceived value of time.

Our system requires an initial schedule as input. This input schedule must include activity descriptions, precedence relationships and estimates of the manhours required for completion. Our system supplements this data with information regarding participant and project goals and resource availability and cost. Our output is a modified schedule, reflecting the results of the time-cost tradeoff analysis. We do not implement a graphical schedule representation. The results of the analysis show up as the values in the activity durations and in the resulting project duration.

Explanation

Because the research project is conceptual in nature, sophisticated graphics or explanation facilities are not a high priority. The prototype is being implemented in KEE. We will use explanation facilities and image panels available in KEE for debugging and user explanation, but will not augment them.

Testing

We will test our prototype with a small (20 to 50 activity) network taken from the project management literature. We will supplement this textbook example with our own data regarding activities, tactics, participants, etc. After proving the concept with such an example, further testing should be done utilizing real project data. The authors anticipate being able to report the results of this testing at the symposium.

CONCLUSIONS

Previous work on time-cost tradeoff analysis suffered from two major shortcomings: the heavy up-front data required and the lack of consideration of the varying goals of the project participants. The work described in this paper contributes to the current state of the art in project management in both of these areas. It provides a solution to the former problem by proposing a richer, knowledge-based description of project activities from which time-cost curves can be deduced, primarily through inheritance; and it addresses the latter problem by explicitly modelling the relationships among project participants to derive the actual time-cost tradeoff facing each project participant.

Future work will concentrate on extending the complexity of the participant relationship analysis, on extending the range of feasible expediting tactics and on integrating JANUS with systems that support other aspects of project management, e.g. generating plans [Darwiche 88] or revising activity durations based on performance [Levitt 85].

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