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A FRAMEWORK FOR INCORPORATING DYNAMIC STRATEGIES IN EARTH-MOVING SIMULATIONS

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ABSTRACT

Earthwork projects involve moving specific amounts of earth from a discrete set of source locations to a discrete set of destinations. Constructors use different methods and equipment to move earth depending primarily on haul distance and equipment availability.

Successful earthwork projects involve successively refined cycles of construction plan preparation and evaluation. The construction plan includes the determination and sequencing of tasks as well as the strategies for allocation of resources among them. The ideal method of evaluating the plan is to simulate models that incorporate the details of the plan and that rely on fundamental engineering analysis and estimated performance, cost and availability of resources.

Current research at Virginia Tech focuses on the development of technology that accurately captures, models, and evaluates the strategic plan envisioned by the planner. This paper presents a framework for the integration of project-level and process-level simulations with the dynamic strategies that form the core of the plan. Obvious benefits that result from implementing this framework include more accurate cost estimation and improved construction performance. The paper illustrates essential concepts with a project involving the extension of an airport runway.

1 INTRODUCTION

Earthwork planning is a science and an art that relies on the experience of the planner. When planning a job, the planner tries to systemically draw up a logical and economical scheme for performing the various earthmoving operations. This overall plan, a reflection of the strategy adopted by the planner, includes determination of tasks to be performed, their sequence, and a strategy for the allocation of resources among the various tasks.

The task of planning an earthwork operation is complicated for various reasons. The nature of the earth and the quantity of work to be performed are associated with uncertainty. The duration of processes that constitute the earthwork operation such as loading, hauling and dumping, are stochastic. Task scheduling is affected by external conditions as well as by resource allocation policies.

In such a dynamic environment, adopting strategies becomes an intrinsic part of the planning process. Hence, simulating a construction operation should include the ability to capture a set of dynamic strategies and represent them on a plan.

2 BACKGROUND

Earthmoving involves distributing specific amounts of earth from a discrete set of source locations to a discrete set of destinations. Usually, numerous combinations of source-destination-quantity are possible. Determining the best combination of such moves is the first step in the planning process. Each move is a task. Different methods and equipment are employed to perform a task primarily based on the nature of the earth and haul distance. Productivity from historical data or standard references for each of the methods provide the duration and the cost of performing the job. External conditions such as project milestones and the experience of the planner drive the sequencing of these tasks.

The effect of human expertise and subjectivity involved in each step is not evident from such a brief description. Selection of tasks, based on simple rules of thumb or elementary calculations, may not be optimal. The quantity or nature (presence of rock) of earth may change, and consequently mandate a dynamic response. Such a change in the scope of the work may alter the sequencing of the job and have an effect on resource allocation. The productivity from historical data typically reflects an average production for different types of jobs under varying conditions. Although such average values may be used as rules of thumb, they typically do not forecast the productivity of crews with precision. A change in the resource allocation policy may also have an impact on productivity. Simulating, and hence estimating, such a dynamically changing environment would benefit from incorporating dynamic strategies.

3 COMMON PRACTICES

Planning and estimating an earthwork operation involves three steps: formulation, representation and evaluation of the plan. Formulation of the plan includes determining the right tasks, sequencing them, and selecting the appropriate equipment fleet. Representation includes a methodology to transfer the plan to a computer model. Evaluation involves actually performing the simulation of the model using a set of parameters and analyzing the performance measures.

Mass Haul Diagrams and Linear Programming models assist in determining the *set of tasks.* A mass haul diagram, a popular method with many contractors, depicts the movement of earth as a function of haul distance. A linear programming model determines an optimal way of moving the earth based on the unit cost of moving earth from each source to each destination. *Sequencing* depends on the resource availability, the experience of the planner, company culture and plain gut feeling. A Critical Path Method (CPM) network depicts the sequence between various tasks. A CPM network consists of both “hard” and “soft” constraints [Chan *et al* 1996]. Physical requirements and external conditions (project milestones) dictate hard constraints. Resource allocation strategies and the general approach of the planner reflect soft constraints. Required production, haul distances and nature of earth drive the *selection of equipment*. The above steps describe the formulation of the plan. Without computer-based simulation, evaluation of such a plan is a laborious or even impossible ordeal. An essential component of the framework presented here is an efficient methodology for plan representation and evaluation.

3.1 Background of Existing Tools

Representing the plan is the most essential component of earthwork planning. CPM networks allow the planner to indicate the physical and logical relationships between tasks. CPM networks, however, exhibit the following limitations:

a) They assume that precedence relationships are fixed and necessary (i.e., all predecessors must finish before the successor can start).
b) They cannot model the interaction, sharing and movement of resources between tasks.
c) They cannot capture the planner's strategies.

Resource sharing and dynamic decisions are essential in an environment fraught with uncertainty. To cope with this, some planners tend to add time to the expected duration of activities to accommodate for uncertainty. Others use tools such as Monte Carlo based simulation or GERT (Graphical Evaluation and Review Technique) [Moder *et al* 1983] to assist in the study of stochastic issues at the project-level.

Various simulation systems have addressed the stochastic nature of project-level construction activities and the interactions between them. CIPROS [Odeh 1992] and AP3 [Sawney and AbouRizk] incorporate process and project-level planning and thereby model the interaction between various processes and resources. These systems, however, do not model dynamic decisions and resource allocation strategies. DYNASTRAT [Morua Padilla 1986], on the other hand, incorporates dynamic strategies for the allocation of limited resources. It scans projects on a daily basis and allocates resources to activities according to the dynamic strategies that have been defined for the project. DYNASTRAT, however, does not actually represent activities with the underlying processes and therefore cannot capture the interaction between them.

4 PROBLEM STATEMENT

The objectives of this framework are to formalize the earthwork planning process and to develop a methodology for plan representation and evaluation. Implicitly, the intent is to integrate process and project-level simulation and to model dynamic strategies. Consequently, this allows a planner to truly represent and communicate the envisioned plan for an earthmoving operation.

Partitioning the problem into three stages gives a better understanding.

1 **Capture the plan**: CPM is a well-established tool for expressing the plan at the project level. Nevertheless, it does not have the capability to clearly indicate both physical and resource precedences. Resource precedence is flexible while physical precedence is rigid. Consider the fragment of a CPM network shown in Figure 1. The planner wishes to indicate that Task C can start with a reduced number of resources (low productivity) as soon as either Task A or B finishes; or that Task C can start with all the resources it needs after Tasks A and B have both finished. A CPM network, however, is only capable of representing the latter. It would indicate that the resources of Task A (shorter) have to wait for the completion of Task B (longer) in order to start Task C. The situation is further complicated if the exact duration of the tasks is not available a priori. In reality, the site superintendent

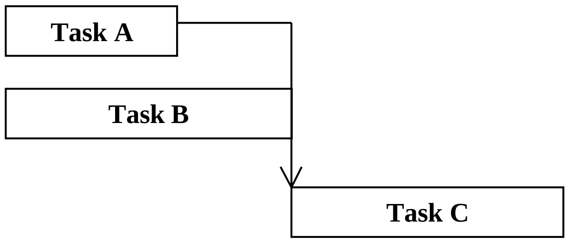

Figure 1: A Fragment of a CPM Network

has to decide between keeping Task A's resources idle and starting Task C with partial resources immediately after Task A is complete. A subsequent section of this paper contains a discussion of the strategies that correspond to such a scenario. This is a clear example of resource precedence not truly concurring with physical or logical precedence.

2 **Represent the plan**: CPM networks depict logical relationships through nodes and arrows. What is necessary is the adoption of a "CPM-like" representation that, in addition to using arrows to indicate physical relationship, employs some method to represent resource precedence. Provisions for representing contingencies or changed conditions should also be present.

3 **Evaluate the plan**: Once a plan has been represented, it must be modeled in a computer so that it can be simulated. For this purpose we use STROBOSCOPE [Martinez 1996] because it is the only construction simulation tool that has the capabilities required to implement our methodology – it was specifically designed for the implementation of methodologies similar to the one presented here. More information about STROBOSCOPE is available at http://strobos.ce.vt.edu. Measures of performance resulting from the simulation such as cost, resource utilization and milestones achieved are used to evaluate a plan. On inspecting the evaluation, the planner may decide to modify one or more decisions or strategies conceived earlier. This iterative process continually refines the plan (Figure 2).

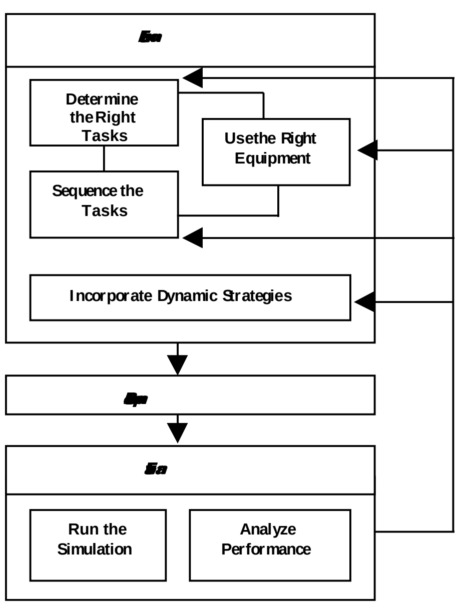

Figure 2: A Schematic Representation of the Problem

5 CURRENT RESEARCH

The success of a plan relies on determining the right tasks, allocating the right resources and reaching all project milestones in time. The right tasks are determined using linear programming techniques while resource allocation and production are studied using simulation.

5.1 Linear Programming

A special form of linear program, the transportation model, is ideal for optimizing the earth movements. The objective is to minimize the overall cost of moving earth. The limits of cuts and fills constitute the constraints. The output of the linear programming model indicates the set of tasks which, when performed, minimize cost. The output of the linear program does not include the sequence in which the tasks should be performed. This sequence has to be determined using external constraints and considering limited resource availability.

5.2 Simulation

The first step is to determine the construction method appropriate for the task, which includes defining the equipment fleet and their expected production -- a function of the expected haul distance. A quick simulation of standard fleets (scrapers and pushers, excavators and trucks) reveals the expected production and cost information. Note that it is not mandatory to use this standard fleet when simulating actual site conditions.

Earthmoving involves three types of work: loading, hauling and dumping. It is important to match the production of the loading equipment with the hauling units to maximize resource utilization. Ideally, the system should suggest to the planner a matched fleet based on haul distances. The planner then decides whether to accept the suggested fleet or to modify it. Human intervention should be present at every step – black-box approaches should be discouraged.

The next step is to create a simulation model based on actual site conditions. The details include information such as haul distance, speed limitations, soil characteristics and other constraints (e.g., road/rail crossings and one-way segments). The dynamic strategies indicated by the planner become part of the simulation code.

6 IMPLEMENTATION

This section discusses how the framework is implemented. For this purpose, we will use as an example, a portion of the airport-runway extension described below and shown in Figure 3.

6.1 Project Description

Federal regulations require that airport runways be free of obstructions for a certain distance from their centerline. The distance is a function of the largest size of aircraft that use the runway. The runway in this case study will be extended to receive larger aircraft. This requires paving 500 feet of runway on the northern end (the earthwork for this part had been done previously); the removal of four obstructions near the runway to meet requirements for minimum unobstructed distance from centerline; the relocation of a channel; and the earthwork for the extension of the runway on the south end (embankment).

The airport must remain operational during construction. Airport authorities have taken measures that give the contractor a 30-day window during which time the 500 feet of runway on the northern end must be paved. The contractor can use one of two routes to move earth from obstruction #1. The most economical route is around the runway. The other, much more expensive route, is around the buildings. The contractor can only use the economical route while the 500 feet of runway in the northern tip are out of service (i.e., during the first 30 days of construction). Any earth movement from obstruction #1 after the initial 30 days of construction must be through the more expensive route.

A physical constraint in this project is that the earth placed in the embankment should in no way obstruct or disturb the channel.

Total project duration must not exceed 140 days.

The portion of the CPM network shown in Figure 1 shows three of the initial tasks in this project. Task A is the removal of obstruction #1. Task B is the relocation of the channel. Task C is the removal of obstruction #2. The task for paving the 500 feet of runway in the north tip is not shown.

6.2 Formulating a Plan

The optimal tasks are determined using a linear programming tool. Due to the 30-day time window, the contractor must begin work on the excavation of obstruction #1 at the outset of the project. In addition, the contractor has to start relocating the channel before placing substantial earth in the embankment. These constraints suggest that the planner should schedule both of these tasks simultaneously. This requires two crews. How the planner will handle the movement of resources as well as provide for contingencies, such as encountering rock, are the essential issues that will be discussed below.

6.3 Dynamic Strategies

A dynamic strategy in simulation is the ability to specify actions based on state variables. This is different from probabilistic branching in which one defines various alternatives at the startup, which remain constant throughout the simulation. This section explains some dynamic strategies that are appropriate for this project.

Sequencing tasks

This strategy allows dynamic changes in the order of tasks as simulation proceeds through time. Consider Task A, which needs to be completed in 30 days. Also, assume that during the first 20 days only 50% of the work is completed due to reduced productivity. Based on the remaining work and the priority of this activity, the contractor can move resources from Task B to assist the resources in Task A in an attempt to complete the work on time.

Alternatively, sequencing can affect the resource allocation policy. Consider the same example. At the completion of Task A, a decision has to be made about its resources – should they remain idle until Task B is completed, or should they start to perform the subsequent task? Assume that the planner does not want to keep resources idle. In that case, two alternatives exist regarding the transfer of resources. The resources from Task A could be transferred to Task B so that it can be accelerated and completed earlier, or resources from Task A could be transferred to Task C, which would start with partial resources (Figure 4). Traditionally, the first alternative is termed as crashing because additional resources are used to speed up the activity. The second choice is more conservative and can be applied when the project is proceeding according to schedule and does not require hastening. This choice may also reflect the attitude of the planner — to allocate minimal resources to more activities and get them started.

Sequencing can also be viewed from the perspective of ease of operation. In the on-going example, consider that the planner intends to work on obstruction #3 ahead of obstruction #4. It is evident that without removal of obstruction #4, the operations may not be easy to handle. Constructing and maintaining a haul road may be difficult. The expected productivity may not be achieved. In such cases, the duration of tasks can be defined as a function of site conditions and work sequence.

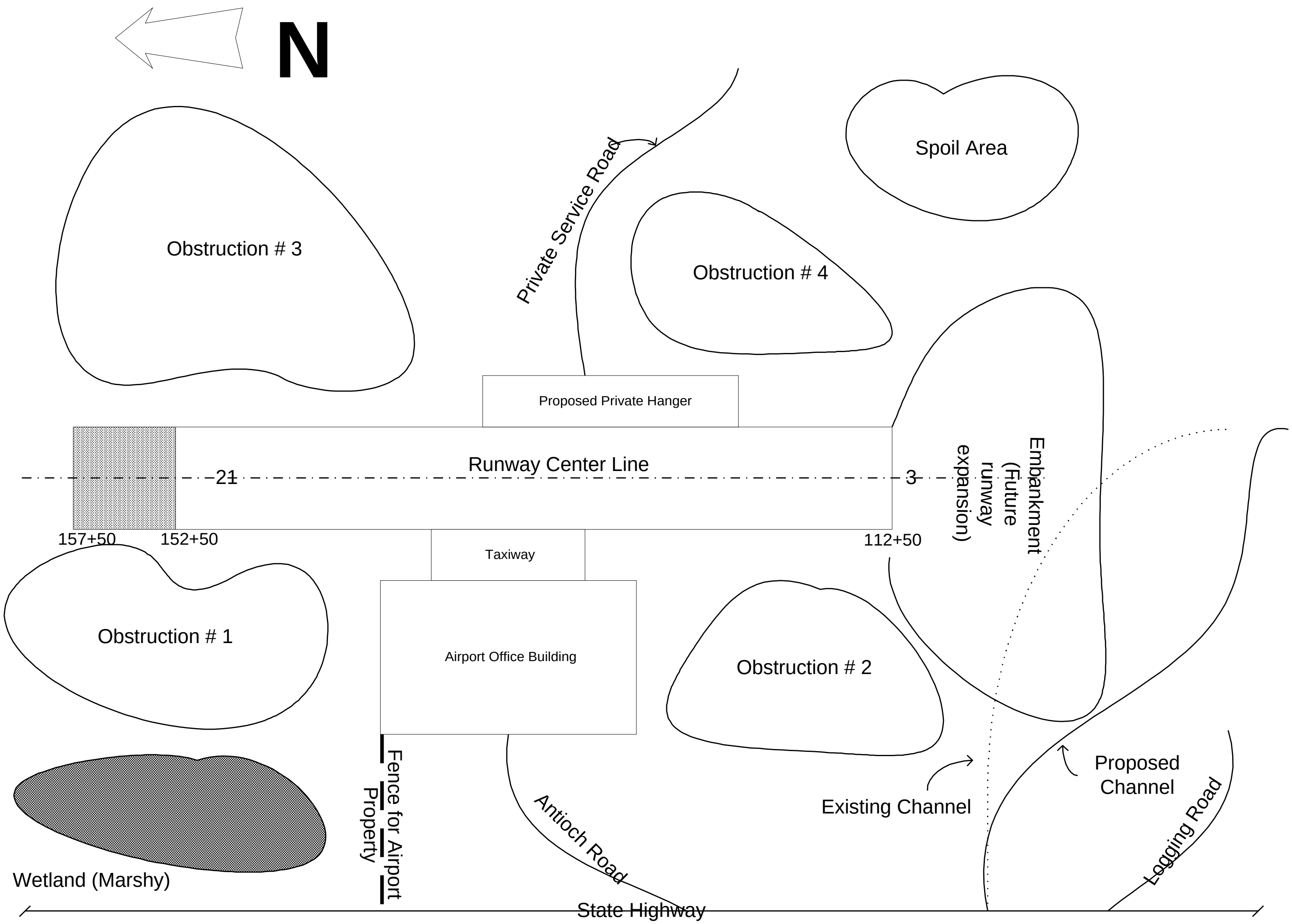

Figure 3: Layout of the Site

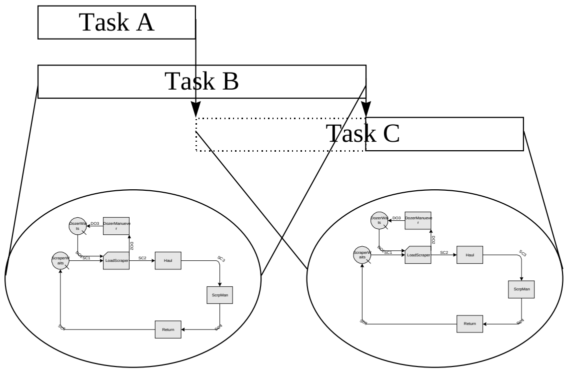

Figure 4 An Example of Dynamic Strategy

Changing resource levels

One need not link resource allocation to sequencing alone. With the same set of tasks and sequence, different resource levels can be allocated to different tasks based on state variables. In some cases, the planner would be interested in knowing the resource-level that should be allocated to the project as a whole. Under such a proactive mode, an unlimited global pool of resources can be defined for the project. When a task is behind schedule and needs to be sped up, the simulation model can allocate resources from the global pool to the task. Consider a task that uses an excavator and trucks. If after a few cycles the state variable describing the average wait of the excavator is larger than a prescribed value, additional trucks can be allocated from the global pool to the task. If, on the other hand, the average wait of the trucks is beyond the acceptable limit, then some trucks can be returned back to the project pool. A plot of the number of resources drawn from the global pool against time will show the resource-required profile for the project. It is then left to the discretion of the planer to use the projected level or to modify it accordingly.

Interruption of activities

Although this decision is not as common as the ones described above, provisions must be made to interrupt activities. The purpose of interrupting an activity is to use its resources for some other activity with higher priority. Interrupting activities can also be incorporated into the simulation model. A sub-net incorporating time for maintenance and repair may be included into the main network. A branching element (referred to as a dynafork in STROBOSCOPE) can inspect each resource flowing through and decide, based on attributes such as hours worked, the routing of resources. If during simulation, for example, a loader is found to be under maintenance, then the trucks can be transferred to another task that can accommodate them.

Reacting to unforeseen events

There are many ways in which models can react to unforeseen events. Excavation, being an outdoor activity, is often affected by severe weather. Uncertainty in the nature of the earth can also be an important factor. Assume that a planner decides to use a scraper for an earthmoving operation and that rock is found on site after a number of passes. The model can be built to react to this event by requesting the services of a rock breaker.

The integration of process and project-level simulation and the incorporation of dynamic strategies allow the planner to represent the plan as per the intent. If the advantage of formulating the plan using a linear programming tool is added to this, it becomes a comprehensive methodology for earthwork planning and a true representation of the overall plan.

6.4 Results and Discussion

The first step involved determining the haul distances for various possible cut-to-fill pairs. Based on the haul distances, the preliminary simulation indicated that a scraper fleet is best suited for all the tasks. The fleet selected for this method consisted of 3 scrapers and 1 dozer. Together they form a scraper-crew. Simulation results also suggested that the production would range from 800 to 950 bcy/hr depending on haul distance. The expected project duration was 144 calendar days (based on the sequence provided by the user) and the expected unit cost of performing the earth-moving operation was $2.42/bcy. The resource usage was 288 scraper-crew days. Note that the preliminary simulation does not include any strategies or details of the site conditions. By using the traditional approach, the planner would have arrived at the bid price based on this cost and a markup.

The preliminary simulation serves two purposes: it provides a baseline for comparison with the proposed approach; it also provides the first guess for the unit cost coefficients for the linear programming model. On solving the linear programming model, a set of optimal tasks were generated (Table 1).

The sequence adopted for the preliminary simulation is maintained for comparison. The strategy discussed in Figure 4 was implemented: when an activity finished, it would start the next activity with partial resources. The duration of the project decreased from 144 days to 138 days, thus resulting in 276 scraper-crew days. The unit cost was reduced to $2.32/bcy. The pusher utilization was 84.07% while the scraper utilization was 87.54%. The activity involving clearing obstruction #1 was completed in 28 calendar days thereby complying with the only required milestone on the project.

Table 1: Optimal Tasks

Activities	Quantities
Obstruction 1 RW to Embankmen	150000
Obstruction 2 to Embankment	190000
Obstruction 3 to Embankment	650000
Obstruction 4 to Embankment	210000
Obstruction 4 to Spoil Area	240000
Chanel to Embankment	180000
Total	1620000

6.5 Analysis

The reduction in unit cost is the result of implementing the overall strategic plan. With typical analysis methods contractors can still conceive simple strategic plans such as the one used for this discussion, but doing so for operations that are more complex is very difficult if not impossible. Even if contractors could somehow conceive such plans, it would be very difficult to represent or evaluate them. Contractors could not ascertain the usefulness of a strategic plan or quantify its effects.

The methodology presented here thus enables contractors to plan their operations better, to assess risks more effectively, and to be more competitive.

The information provided by incorporating dynamism in simulation allows us to evaluate various strategies. We could go back and modify one or more decisions. This could include changing the tasks, modifying the strategy to transfer resources, or changing the level of resources. By repeating the steps described, the user is able to successively refine and improve the overall plan. Additionally, we could also use the sensitivity analysis feature of the linear program to study how the cost would be affected by a change in parameters. It is common for contractors to realize that the actual quantity of work may increase or decrease from the values given in the proposal. The presence of rock may require the use of a different method and the unit cost of performing the job may result in a different basis for the linear program solution.

7 CONCLUSION

The goal of the methodology described in this paper is to improve earthwork planning and estimating. This is achieved using linear programming and simulation. The key feature is the ability to incorporate dynamic decisions. The product, an efficient and optimized strategic plan, reflects the way the project will be built on site. The paper also presented a discussion on the current techniques and the drawbacks of using CPM networks to accurately represent the intent of the planner. An airport runway extension was used to illustrate the essential concepts of our framework. Future research could involve linking this system with external programs that assist in quantifying the work.

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