CONSTRUCTION SIMULATION RESEARCH AT THE UNIVERSITY OF MICHIGAN

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Introduction

The paper summarizes three current research thrusts at the University of Michigan to advance the state of the art of computer modeling of construction. They can be classified as (1) process simulation, (2) project simulation, and (3) project time-cost tradeoff. The research was born out of a concern for the limited capacity of available techniques to model construction realities.

Construction managers select methods to assemble material resources using human and equipment resources. Tasks are linked as activities, which are performed in a sequence dictated by physical and resource constraints. Objectives in selecting alternative methods and resource assignments are to complete the project quickly and inexpensively. Most human and equipment resources and methods are shared among several activities, as are supervision, weather, and other duration and cost related variables. Some of the variables, such as construction methods and personnel and equipment assignments are selected by managers and are therefore decision variables. The magnitudes of other variables, such as crew and equipment productivities and weather, are uncertain and can be considered selected by nature and are therefore random variables.

In reality, managers make decisions as they are needed, based on progress and information available to date, and they monitor the actual progress which results from those decisions and provides information for their next decisions. Managers' decisions depend upon outcomes of random variables which precede them, and the decision variables can therefore be considered random variables themselves. The realization of a project can be modeled as an interrelated set of decision and random variables. Even on well planned projects, original resource assignments will change during construction to reflect actual conditions and experience as construction progresses.

The research at the University of Michigan models these construction realities by its general focus on these items:

(1) Identification and characterization of independent random variables and decision variables, such as methods, resources, management, and weather.

(2) Cost and productivity functions of construction, as related to the random and decision variables.

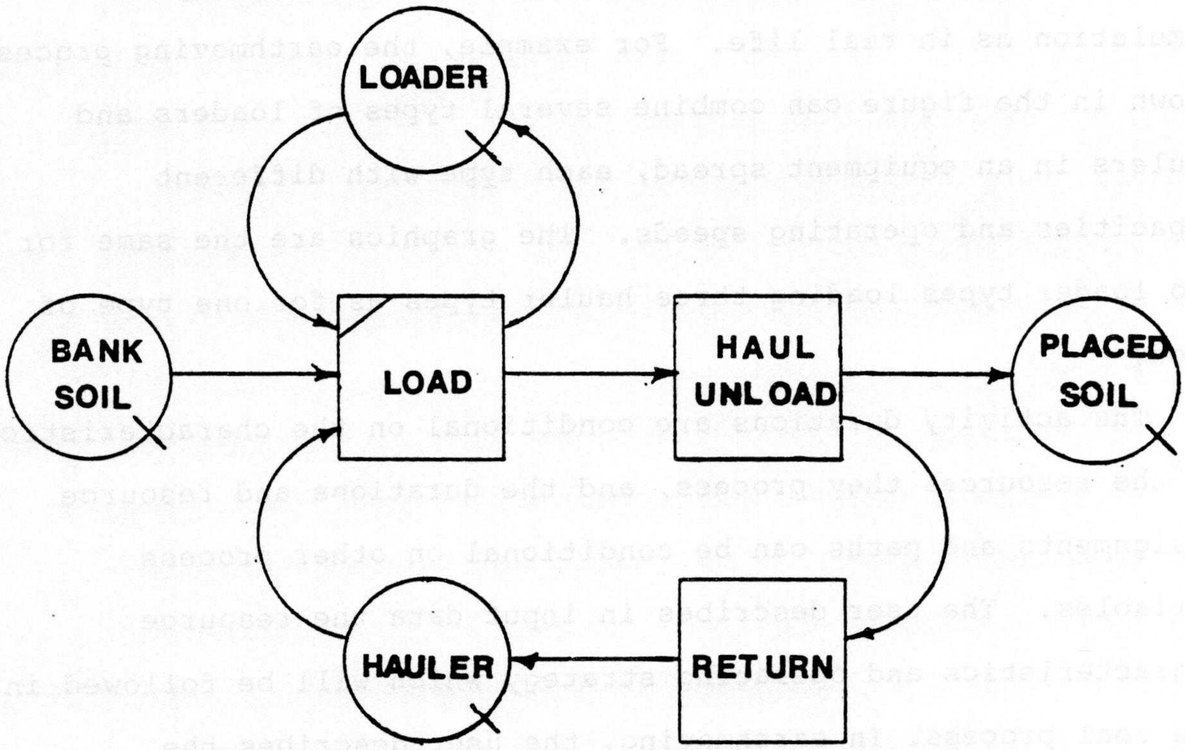
(3) Relationships between independent variables and process and project duration and cost.

(4) Dynamic nature of construction and decisions required during construction.

Construction Process Simulation - RESQUE.

The process simulation model, RESQUE (or MIRESQUE), is a resource based discrete event Monte Carlo simulation program which is designed to model construction processes. The resource flow patterns in RESQUE can be simply shown with CYCLONE queue and activity elements. However, a resource based data structure underlies the CYCLONE element relationships. This allows RESQUE to model the mixed resource and strategy processes which are typical of construction. CYCLONE is limited to element relationships and has a difficult time with mixed resource and strategy processes.

The figure below shows a CYCLONE representation of a simple process for loading and moving earth. The Combination, or Combi activity (rectangle with diagonal in its upper left corner) is the fundamental element of CYCLONE and RESQUE, because it models a resource constrained operation. Loading a hauler with soil obviously requires both a loader and a hauler. A Combi activity is started at any time its resources are available.



Resources must be accounted for at all times. If not involved in an operation, they are in a Queue (shaped like a Q). A Queue element holds a resource type waiting for other types of resources to be available to start a Combi. Only Combis can follow Queues, and Combis can only be preceded by Queues. An operation which will always immediately follow another can be depicted as a Normal activity (rectangle without diagonal). A hauler will return to the loading site whenever it has finished unloading, and its return is shown as a Normal.

A RESQUE user (a resquer?) can characterize individual resources, and RESQUE queues and activities can differentiate among resources so that different resources (such as different sizes of tractors or trucks) can be treated differently in simulation as in real life. For example, the earthmoving process shown in the figure can combine several types of loaders and haulers in an equipment spread, each type with different capacities and operating speeds. The graphics are the same for two loader types loading three hauler types as for one type of each.

The activity durations are conditional on the characteristics of the resources they process, and the durations and resource assignments and paths can be conditional on other process variables. The user describes in input data the resource characteristics and operating strategy which will be followed in the real process. In earthmoving, the user describes the distribution of cycle time for each loader model and the number of loader cycles for each match of loader and hauler. The user also establishes the operating strategy for matching loaders and haulers in the load activity. Alternative process plans can therefore be described and evaluated without disturbing the simple, easily understood graphical description of the process.

We have designed all of these characteristics into RESQUE. We are now working on the most complex item we have run into: a general representation of hierarchal resource sets, such as a truck carrying a mixture of items in different containers. Such a set could be a truck, driver, varied containers, and varied items in the containers. We allow a Queue to serve a variety of activities each of which processes a different type of resource from whatever sets of resources are found at the Queue.

RESQUE is being developed to overcome the difficulties which CYCLONE has in handling construction processes which have a mixed resouces or conditional strategies. In CYCLONE, each element can only model one resource type or one set of resource types, and relationships among elements can only be represented by the CYCLONE elements. Mixed or dynamic strategies, such as mixed equipment spreads or dynamic operating plan or conditional durations, become graphically complex and difficult to draw or understand. Yet each of these is typical of construction processes.

For example, if more than one type of loader or hauler is used in a spread, the earthmoving process in the figure becomes quite complex with CYCLONE. If only one loader type and one hauler type were used, the process would be as shown in the figure. However, if the number of hauler types were increased to two, of different capacities, the graphics explode from 7 elements and 8 arcs to 21 elements and 28 arcs. The CYCLONE model of two types of loaders and three types of haulers becomes impractical. Yet, the process itself, except for the matching loader and hauler types, is no more complex for mixed types than for single typess.

RESQUE can handle the complexities of mixed strategies and resources by separating them from the graphics. They are no longer hardwired into the model. They can easily be varied to test sensitivities, as is typical for simulation. The data format lends itself to interfacing with automatic real time data collection and analysis or with interactive programs. We expect RESQUE will evolve into a key component of active process control and knowledge based system planning of processes.

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<u>Construction Project Simulation - DYNASTRAT.</u>

DYNASTRAT (DYNAmic STRATegies) integrates detailed estimating of cost and time, Monte Carlo simulation of durations, resource allocation, and system dynamics for construction projects. It is a more realistic model of project duration and cost under uncertainty, the first to recognize common dependencies among activity costs and durations, the first to recognize the dynamic nature of management decisions, and the first to analyze alternative resource strategies for managing projects under risk.

The project simulation is built on the framework of MUD, which models project progress and duration using Monte Carlo simulation. MUD requires the user to (1) identify independent random variables which control project duration, (2) estimate probability distributions of the independent random variables, and (3) estimate relationships between independent random variables and activity durations. This treats the problem of correlation between activity durations, and costs, by recognizing their common or shared dependencies on independent random variables.

For example, painting on the second floor is correlated with painting on the third floor, because they share the same crew. This correlation can be effectively modeled by identifying painting crew productivity as an independent random variable, estimating its probability distribution, and relating it to the two activities. Another independent random variable is weather. It is simulated by DYNASTRAT, and its impact on activities which share its effects are also simulated, using sensitivity factors similar to those in MUD.

DYNASTRAT extends MUD by requiring characterization of activity resources and their related costs and productivities. It can therefore simulate activity and project direct and indirect costs as well as duration. For example, the painting crew is made up of painters at x dollars per day each and a painting machine at y dollars per day. The relative productivities of 3, 4, 5, and 6 painters per machine can be estimated. The number of square feet of painting, the gallons per square feet, and the cost per gallon can be estimated. Any of these can be considered random variables and estimated as probability distributions. Sampling of random variables, assignment of number of painters to crew, and simulation of painting duration can be translated into direct cost of painting.

Construction projects are dynamic, changing from day to day, and plans require adjustment to fit new information and changes. This is particularly true on projects on which times and costs are highly uncertain. Primary management decisions concern the procurement of resources and their assignment to activities. The criteria for procurement and assignment are duration, cost, and criticality, and these criteria are uncertain on uncertain projects. In a building, if HVAC installation has difficulty, painting may not be critical, and a small number of crews sized for maximum productivity may be best. However, if HVAC goes smoothly, painting may be critical to completion. In this case, additional crews or full, more expensive crews may be selected to save indirect costs of finishing the project later. Likewise, if the productivity of the painters is uncertain, the number of painters per crew and the number of crews may be adjusted as the work progresses to fit the actual painting productivity experienced. High painting productivity may be met by lowering the number of painters if painting is not critical or by adding painters if painting is critical. The assignment of painting crews, and resulting durations and costs, are dependent on actual site conditions experienced and are therefore uncertain.

Previous models of uncertainty, including MUD, have not recognized the decision dynamics. They have not recognized (1) resource limitations, (2) changes in assignments to meet changed conditions, and (3) relationships between activity duration and resource cost. The addition of the resource and cost detail allows DYNASTRAT to include day-by-day resource assignment decisions during construction, based upon the experience to date on the project and prediction of future performance. We find ourselves breaking new ground, because no one has modeled resource allocation under uncertainty.

Todays resource allocation strategies are designed for deterministic durations and costs, not uncertain durations and costs. In an uncertain project, not only are activity durations and costs uncertain, but activity early starts, criticality, floats, and future resource assignments are uncertain. And these are the criteria used by resource allocation models. Our major effort with DYNASTRAT is to develop a conceptual framework for identifying reasonable dynamic management strategies for resource allocation decisions during progress of uncertain projects. Key input to decisions are progress to date, information to date on outcomes of random variables, and estimates of future outcomes based on past simulations. A strategy includes not only heuristics for procuring and assigning resources, but also for selecting information to gather to make decisions and intervals of updating such information. When managers develop plans and estimate project cost and duration, they can test and evaluate alternative real time decision strategies and consider the positive effects produced by such adjustments during construction.

In summary, DYNASTRAT makes these major contributions to construction management technology: (1) It establishes a framework for selecting dynamic resource strategies for uncertain projects. (2) It simulates real time resource decisions in managing construction projects so that simulation results are realistic. (3) It provides a model of time and cost for uncertain projects, which considers shared dependencies on independent random variables. Eloy Morua is the doctoral student performing the primary research on DYNASTRAT.

DYNASTRAT provides a first look at analysis of construction project dynamics for uncertain projects. As we research dynamic, real time decision strategies, we can expect to develop knowledge based systems for dynamic management of uncertain projects. Many people feel that the most characteristic property of construction projects is their dynamic character: they change. Our management tools need to allow for change; in fact, they need to be built around change if they are to correctly model and mold the construction process.

Project Time-Cost Tradeoff.

Construction time-cost tradeoff methods have neither grown in sophistication nor in realism in twenty years. They require an estimated duration versus estimated cost curve for each activity in the project. This is combined with a description of precedence among activities which identifies the activities which must finish before other activities can start. Regardless of whether the solution is by hand or by computer, the procedure is to determine which activities are critical to the duration of the project and determine which can be shortened such that the project is shortened at least cost. The selection is among sets of critical activities according to their time-cost curves.

Such time-cost tradeoff is accurate only where no shared methods or resources are changed during time-cost tradeoff. Of course this does not recognize that typical construction activities share methods and resources. Therefore, classical time-cost tradeoff procedures are not useful for most projects. One example of the shared methods is a cast-in-place reinforced concrete bridge of several spans. Erecting formwork for each span is an activity. If on-site fabricated wood forms are used for one span, they will be used for all; if prefabricated steel forms are used for one they will be used for all. Neither assigning the cost differential to one of the activities nor splitting the total cost among all sharing activities is correct, because either all change or none change. Similarly, many activities may depend on sharing a crane. If a larger crane or a second crane is brought onto the site, all of the activities will be affected in their durations. However, the cost of the change in crane can neither be assigned to one activity nor split among all, because they all change together.

The key to a realistic solution is to focus on the methods and resources themselves, rather than the activities which show their effects. For each shared method or resource there is a set of corresponding time-cost curves for affected activities. Because the major time-cost decisions are method, resource, or shift related, the activity time-cost curves can become secondary to the method, resource, and shift related costs.

The doctoral student who is performing the research, Rehab Reda, has formulated the problem as a mixed integer program with 27 basic constraint equations. Of these constraints, 2 are common to all activities, 2 treat method related activities, 4 are related to shared resources, 18 are related to selection and timing of a multiple shift period, and 1 sets a target duration for the project. The mixed integer program selects the optimum configuration of methods, resources, shifts, and activity time-cost tradeoff curve positions for each trial target duration. Running the program for the range of possible durations produces a set of points which describe the lower bound of cost for each possible duration of the project.

The new time-cost tradeoff model evaluates alternative methods, resources, and shift adjustments which determine duration and cost of activities and the project. Time-cost tradeoffs are between methods, resources, shifts, and all decisions are between realistic plans. In contrast, past computer time-cost models have neglected shared methods, shifts, and resources, and have been realistic only at the starting point.

<u>Summary</u>

The three models extend realistic modeling of construction to allow better evaluation of decisions and provide the users with a better understanding of processes. They are more robust in their characterization of processes and lead toward integrated models of construction. The detailed analysis of processes integrates well with introduction of robotics and design of roboticized processes and can provide a foundation for more sophisticated construction management decision support systems.