Proceedings of the 1988 Winter Simulation Conference
M. Abrams, P. Haigh, and J. Comfort (eds.)

Large project simulation: A powerful tool for project management analysis

Charles S.Ondash and Stephen Maloney
Devonrue, Ltd
180 Lincoln Street
Boston, MA 02111

Juan M. Huerta
PDMI
235 Concord Ave.
Lexington, MA 02173

ABSTRACT

This paper presents the effects captured by dynamically simulating large complex projects. The simulation is accomplished by developing standard commodity modules which are then linked. Traditional dynamic simulation languages can be used or the modules in C-enhanced user interfaces can be deployed.

THE GROWING NEED FOR LARGE PROJECT SIMULATION

Over the past thirty years, project management has undergone significant growth and development. Fueled by a major expansion in technological complexity, more sophisticated planning and project control aids have become necessary simply to keep up with the needs of industry. Today, no single large engineering project begins unless accompanied by extensive planning and task scheduling. Yet, as projects have grown larger and more complex, it has also become evident that they are increasingly susceptible to cost and schedule overruns due to external disruptions. Such overruns were generally undetected by critical path models until they became unavoidable. By the time the overrun potential was identified by the project model, managers quickly found themselves immersed in a "fire drill" atmosphere from which there was little opportunity for escape. Turning to their critical path models, managers demanded more detail and more frequent project information and planning, often at increasingly greater cost. By that time, traditional management tools offered little to reduce the potential for overruns. To many practitioners, it appeared that the practical limits had been achieved with computer-based critical path project planning.

While project managers have long recognized the direct and ripple effects due to changing requirements, the traditional planning and cost control tool --- the computer based critical path model --- has been of limited value in demonstrating those effects. The need for more powerful project management tools has led to the development of a new modeling technique to complementing the traditional critical path project model. This new area, dynamic project modeling, offers a faster and more accurate representation of the resource and information flows of a large, complex project than is available from critical path models. Devonrue has pioneered the application of dynamic project simulation to large complex engineering and construction projects through the use of Large Project Simulation (LPS) modeling.

Devonrue's LPS dynamic models are mathematically simple and afford a practical, rigorous way to articulate the complex changes in a construction project to both a practitioner and the layman. When applied to project models, dynamic models offer three benefits of value in construction claims:

- quantifies the ripple effects due to external change;
- illustrates the natural limitations of management decisions in preventing overruns caused by changing external requirements; and,
- complements traditional critical path methods by graphically explaining overruns to laymen.

Quantifying Ripple Effects.

A unique feature of dynamic project models not offered by network planning methodologies is the ability to calculate the ripple (secondary) effects on project cost and schedule due to changing requirements. These changes might include changing government regulations, changing client needs or changing workforce availability. Ripple effects occur in labor productivity, unanticipated schedule slack and float time, and resource availability constraints resulting from unanticipated production changes. These processes can only be modeled by using dynamic modeling with explicitly represented feedback mechanisms. In this respect, dynamic project models complement the static critical path models by providing the capability to readily perform sensitivity analyses of likely perturbations and their consequential ripple effects.

Natural Limitations to Management Decision in Preventing Overruns.

CPM/PERT models monitor individual engineering and construction tasks (i.e., the discrete pieces of work required to complete the project). If all the tasks are completed, the project is complete. The LPS model captures the measures of the activities which produce the tasks. If one were focusing on the engineering portion of a project, the measurements would typically include a complete set of basic engineering products, such as the number of drawings, specifications, calculations, etc. If one were focusing on the construction portion of a project the measurements might include cubic feet of concrete ready for pouring, cubic feet of concrete poured, cubic feet of concrete removed and replaced, etc. This approach directly models the work process, bypassing the cost accounting and scheduling representation of the project. Although the model also tracks the project's task for scheduling purposes, actual costs can be directly calculated as they are incurred in the production of the various engineering products.

Dynamic project models represent the flow of information, resources, and products on a project. These flows are portrayed at an aggregate functional level-- such as man-hours expended by civil/structural, mechanical, or electrical engineers in a given work phase--rather than attempting to follow the discrete organizational structure and individual task definition used to manage the project. The flows are modeled through a detailed series of difference equations which are solved by the computer in discrete time steps, providing a time-based representation of actual and projected costs and schedules.

The traditional approach to forensic (e.g., what went wrong) critical path methods involves an expensive reconstruction of the various critical paths which existed at different epoches over the life of a project. Project data is reviewed and placed in "bins" which define allocated man-hours. Project cost records are then analyzed by experienced engineers who proceed to re-assign man-hours from the project accounting system to the various newly-defined bins. One weakness of the "bin analysis" technique is that it often falls short of fully quantifying the impacts of change because the bin contents are synthesized from project data assuming constant productivity. Hence, a significant portion of an impact may be overlooked, such as reduced productivity in other disciplines or additional overtime costs incurred in "crash" tasks. In contrast, dynamic project models distill an impact by recreating the project in a computer simulation. The value for the layman in this approach is the simplification of large scale construction project complexities and the presentation of analysis in a graphic form.

WHERE LPS PERFORMS AND CPM/PERT DOES NOT

Two reasons highlight the advantage of using LPS over the traditional CPM/PERT methods to analyze large construction projects with continuous disturbances. The first basis deals with CPM/PERT's computational difficulty of obtaining "unbiased" estimates for the duration of activities in a network due to the inherent assumption of zero variability in task time duration. The second basis reviews how CPM/PERT, which are "static" methodologies, do not deal with the nonlinear production rates and other dynamic characteristics of a large scale project.

Inherent Assumptions of Zero Deviation to Task Duration

CPM techniques assume that each task has a set duration. In determining the project critical path, the duration of the tasks are not allowed to vary. A set, logical sequences of tasks is determined. All task durations are added for these logical sequences. The longest combination of logical sequential task durations is the critical path.

Schonberger has provided an example of the theoretical bias of the assumption of zero duration variability. He examines the simple case of two parallel activities, each with a duration of five days. If no time variation of the task duration is assumed then the project duration is five days. However, if the duration of the task is allowed to vary plus or minus one day (i.e., four, five, or six days, each equally probable), a Monte Carlo simulation will show that the mean project duration is 5.4 days. If more variability is added (e.g. five plus or minus two days each equally probable), the mean expected project duration is 5.8 days. Shonberger goes on to make some general conclusions:

(a) the larger the task-time variability, the later (than CPM determines) the mean project duration; and,

(b) the fatter the network (the larger the number of parallel tasks), the later the mean project duration.

In a similar way, Klingel provides a more sophisticated analysis for the large PERT network. PERT networks account for task time variability by allowing each task to have a best, worst and most likely durations. These three are combined for each set of logical sequences of tasks to determine the most likely project duration. The networks examined by Klingel, is as follows:

> " A Network comprised of multiple restaurant-service station installations offered for flexibility of study while still preserving reality. Ten installations were diagrammed in parallel, including elements from market research, site selection, property surveys, zoning requirements, etc., through construction, hiring of personal, installation of equipment, to actual opening for business. Each installation required about one hundred elements. In addition, about one hundred elements common to all restaurant tied the ten parallel installations together with common constraints. These comprised such items as ordering consumables,

> warehousing systems, developing accounting procedures, advertising campaigns, etc. With nearly 1,100 elements, it was felt that the network was large and complex enough to give results which would not be too easily predicted."

Klingel was interested in examining the effect of project duration on the numbers of parallel paths and the time variance on the individual tasks. The number of parallel paths was varied by changing the number of restaurant installations. The task time variance was examined by generating normal random deviates for a given set of Fisher's coefficient of variation (0, 1/6, 1/3, and 1/2). Twenty-five runs were calculated for each scenario, varying the numbers of restrained installations. The cases represent one through ten restaurant installations.

The results showed that the project completion time increased over PERT - predicted completion times as both the number of installations (number of parallel paths) and the coefficient of variations (i.e., task time variability) increased. The increase for each variable was both non-linear and dependent on the other variables. In an attempt to understand these correlations Klingel performed a set of numerical methods, curve fitting analysis and derived a set of equations graphically representing the dependencies figuratively present in Figure 1.

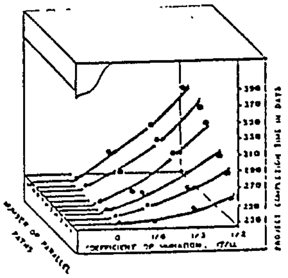

Figure 1

As described above from a theoretical basis, Shonberger and Klingel demonstrate that CPM/PERT networks have inherent weaknesses as the number of parallel paths and time activity variable increases.

Methods suggested by the authors to overcome the underprediction of project completion durations by CPM/PERT include having the project manager (a) always assume the CPM duration is wrong and (b) subjectively reevaluate the project duration on a continuous basis. Basically these solutions ask the CPM/PERT practioners or users to recognize the inherent bias of CPM/PERT techniques. From a practical point of view, this is possible in some situations. However, when large projects are involved, even the most skilled practioners's instinct may not be enough to capture complex second and third order effects.

Inability to Account for Non Linear Product Rates and Feedback.

In addition to the above discussed theoretical limitations, CPM/PERT methods are limited in their ability to account for non linear production rates and feedback. CPM/PERT assume a constant production rate for a given task. For example, CPM might assume each drawing requires 50 engineering man-hours. A given task might be to produce a 100 civil structured drawings in 3 months. In reality, the number of engineering hours to produce a drawing may be a function of (a) the experience level of the engineers, (b) the time within the task at which each specific drawing was started, (c) the amount of overtime worked, or (d) the rate at which engineers were added or deducted from the task.

Huot has performed work examining the dynamic aspects of large projects. He examined one well documented characteristic of large systems: the persistent dynamic tendencies which arise from the system causal structure. This characteristic is often imposed on the project by constraints such as labor availability, management policies, and government requirements. Traditional methodologies do not cope with delays and disruption costs since they are typically task oriented. They are less effective in anticipating and planning for indirect, second, and third order "ripple effects" produced by disturbances. These are snowballing scope expansions, schedule additions, and production inefficiencies. They may occur within a work phase or between construction subprojects as a result of altered work sequences, conflicting facilities and manpower requirements, skill dilution, and undetected work errors.

In real life, a construction process requires many types of inputs over the duration of an activity to produce an output which may be distributed over time. The system methodology discussed above models real life processes in terms of inputs, transformation, outputs, constraints, and interactions. In addition, the time to complete an activity is computed in the duration of a process as the activity moves toward completion.

Traditional CPM/PERT methods usually describe an activity in terms of duration and costs. Unit rates are constants derived from historical data. In the analysis of impact disturbances, we are concerned with how project management can effectively utilize inputs and transformations to ensure that the phases of a project or subprojects are working effectively and the project is on schedule. The richer structure provided by the systems methodology enables us to operate on a "what if" mode to test the impact of alternative strategies by changing inputs to the processes and rates of production. For example, if we want to contain a disturbance by minimizing its impact on a critical activity, we may try to "compress" the activity. CPM/PERT offers trade offs between cost and duration (the shorter the duration, the costlier the activity). However, they do not easily represent inherent non linearities typical of these trade offs. Furthermore, they do not allow technology changes or organizational changes which may be necessary to complete an activity within schedule.

HOW AN LPS MODEL IS CONSTRUCTED

In order to obtain an appreciation of how LPS overcomes the limitations of CPM/PERT methods, an understanding of how LPS models are constructed is essential. In order to analyze the impact of complex issues on large scale, multi-billion dollar construction projects the project is defined in terms of:

(1) transformations of ideas, materials, and energy into generalized interlinked commodities; and,

(2) organization of these commodities into phases or blocks to orderly proceed from design to detailed design to procurement to construction.

Processes can be defined in terms of input flows of energy, materials, etc., that are transformed by people and machines to produce finished products as outputs. These finished products can be completed designs, finished construction, etc., depending on the phase of the project .

From Figure 2, it is apparent that the amount of output over time depends on the inputs and the transformation process. For example, if we increase the number of engineers working in design phase, we can expect an increase in the output per unit of time. This rate of production, however, tends not to be linear. That is, if we double the number of engineers, we do not necessarily double the output. Furthermore, if we increase the number of engineers without regard to working space requirements, we would be creating an additional problem of congestion that usually reduces the engineers' efficiency and, consequently, their output rate. Even assuming that problems of congestion do not exist, engineers would be hard pressed to produce if a backlog of preliminary designs does not exist.

Where Figure 2 presents the generalized concept of how a project is viewed by LPS, Figure 3 depicts a more concrete example of a model that represents the transformation of ideas to output. This figure presents a typical design process which involves a conceptual or basic design followed by a detailed design which is in turn used for procurement and or construction activities. Conceptual or basic design precedes detailed design. Changes to the conceptual design can occur after completion of conceptual design but before detailed design is initiated, after detailed design is complete, or prior to procurement or during the procurement/construction process. The conceptual design is performed by engineers. The detailed design is performed by junior technicians or draftsman. For a large project there may be any number of basis building blocks. For example, each discipline-civil, structural, mechanical , electrical, etc. - could be modeled as a basic building block.

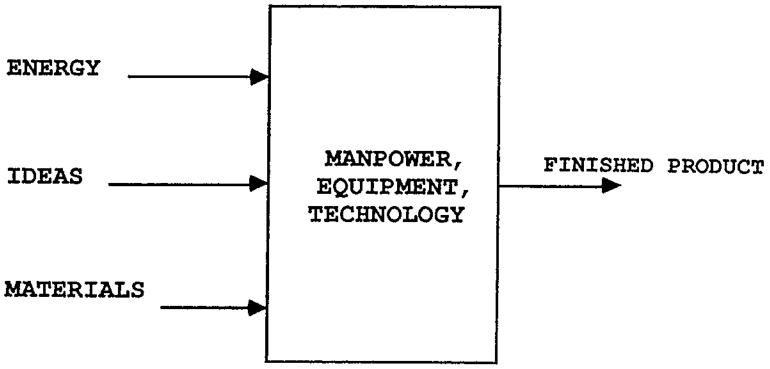

Figure 2

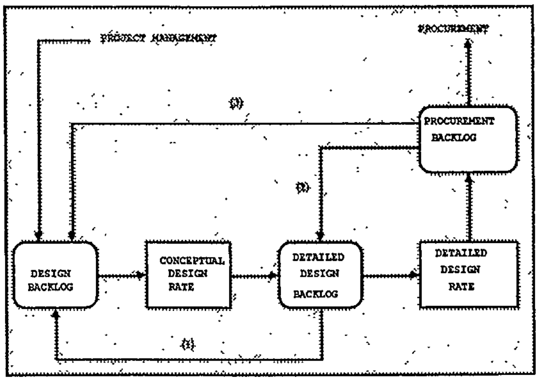

Figure 3

For this basic building block the following observation concerning the flow of work can be made:

- Project Management determines the size of the Design Backlog at the onset of the project. This backlog is transformed, by design engineering, into detailed design at a rate per day.
- A portion of the detailed designs are returned to the Design Backlog(loop 1) to be reworked. The rest are transformed by engineers and draftsmen into detailed design, at a given rate, to become the Procurement Backlog.
- A portion of the Procurement Backlog is rejected to be rework again by detailed design (loop 2) while an other portion is returned to Design Backlog (loop 3). Approved detailed design continues to procurement.

For this simple building block many non linearities can arise. The Conceptual Design Rate may not be consistent with the Detailed Design Rate causing the Detail Design Backlog to increase or decrease over time. The rates - Conceptual Design Rate or Detail Design Rate - may increase or decrease independently over time based on the availability of engineers, technicians or draftsmen. The Procurement Backlog, which is rejected to be reworked by Conceptual Design might occur when there are no engineers available due to project destaffing or utilization on other work efforts.

Design Backlog is usually planned assuming a constant decrease. In reality, it may vary. Under the stress of a disturbance, such as the re-design of some portion of the project, Design Backlog may increase considerably. In that case, design engineering becomes the bottle neck that slows down the progress of the project. As other phases (such as procurement and construction) are coupled, the level of complexity produced by the dynamics of the situation may increase dramatically.

The building block process in Figure 2 is termed a "commodity flow module" in LPS terminology. The commodity represented is engineering drawings. Of course, many commodities are represented in a large complex project. Table 1 lists some typical commodities that can be represented in a project.

The commodities are chosen based on the problem being analyzed. The number of commodities used in a model can be as varied as a function of the problem being analyzed. Typically, a number of commodities are chosen based on modeling experience. A first cut model is developed. As the results are reviewed, a decision can be made as to where greater detail of commodities is require. This "top down" approach provides great flexibility in the development of the final model.

TYPICAL COMMODITIES
Engineering Drawings
Engineering work packages
Concrete
Structural steel
Large bore pipe
Small bore pipe
Fill
Startup work packages
Field change notices
QA nonconformances
System turnovers

Table 1

For example, using a number of commodity blocks, a dynamic macro-engineering model that measures output in traditional terms of bulk commodities (the output of an engineer is "x" tons of structural steel a day and that of a construction worker is "y" tons of concrete a day) is built . This enables the user to visualize the impact of changing rates of output, shortages of material, etc. The model becomes more sophisticated when elementary transformations are considered as part of organized phases in the construction project, such as design or detail design and the overlapping between commodities. One additional refinement necessary in the model has been matching the commodities with engineering skill requirements (such as structural engineering or mechanical engineering) and considering engineers at junior and senior levels.

Quantifying impacts that disturbances produce in a project organization requires knowledge of (1) where and when within the boundaries of the system the disturbance is introduced, and (2) what is the expected duration of the disturbance. With this information and a dynamic model of the project organization, we are able to simulate the scenario of disturbances and learn (1) how the individual subsystems react, and (2) how individual subsystems reactions propagate to other subsystems within the project organization. This is achieved by incorporating "policy modules" into the model. Policy modules represent policies which affect the method in which the project is structured and in which the commodities are liked. For example; Federal, State, or local government standards all affect the project methods and structure. When government policies (i.e., new regulations) are issued, the effect of this disturbance on the project can be observed. Thus, the analysis of impact requires the modeling of disturbances as well as the processes taking place in the organization. Figure 4 depicts the interaction between the basic commodity modules and the policy modules.

The three boxes in the Figure 5 diagram represent resource inventories for the number of staff engineers, the number of experienced engineers, and the amount of work completed. The rate at which resources accumulate is controlled by "rate-terms" (represented here by the circular symbol in the pipe stream). They are also consistent with the resource flow analogy. For example, the experienced engineers enter from a "cloud" (acquired from elsewhere in the model or externally), and accumulate at a rate governed by the "experienced engineer acquisition rate". Experienced engineers leave the project at a rate controlled by the experienced engineer attrition rate. Similarly, the inventory of completed work is constantly built up, controlled by the "work completion rate".

The attrition rate is controlled by other factors (represented by circles connected by arrows to the attrition "rate-term"). For example, the quantity "supervision level" is a function of the number of experienced engineers. In this simple model, the supervision level is shown to affect the complete work rate through the overall productivity term. Similarly, the amount of work completed is shown to affect a term referred to as "schedule pressure". This model uses schedule pressure as one influence controlling the staff of engineers available to perform work. If all the relationships presented in the diagram are traced, it can be seen that many factors influence or "feedback" on the rate and quantity of project resources in a complex manner. Such complexity reflects the difficulty real managers face in controlling a project.

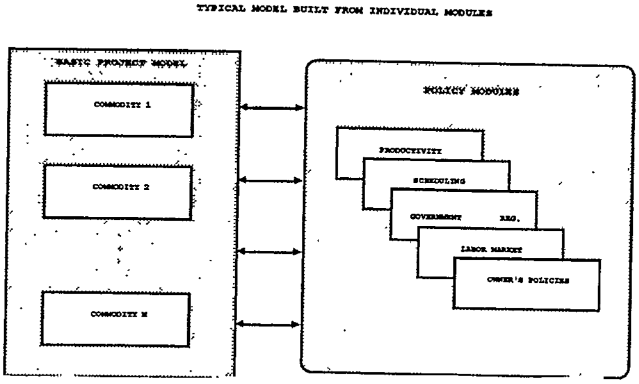

Figure 4

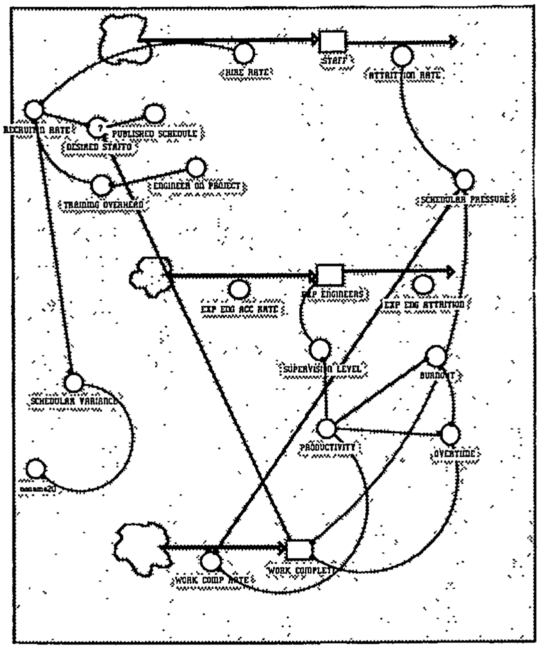

Figure 5

AN EXAMPLE: PROJECT MANGEMENT ANALYSIS OF A LARGE POWER PLANT

An example of the use of a LPS model is often useful in obtaining an understanding of the results of LPS. This example is derived from an actual case study which examines the impact of changing government regulations affecting the design of a large power plant. To illustrate the principle of a dynamic project model, a simplified representation of some of the managerial considerations affecting the engineering aspects of the project is presented in Figure 5. Three terms are particularly important to the flow of work on a project: staffing, aggregate work, and productivity.

This model illustrates the basic flow of work on an engineering project. It is provided only to introduce the conceptual basis for dynamic models. Actual project models consider a far greater number of factors and their interrelationships. These relationships are translated into difference equations for a time-dependent solution by computer simulation. The product of the simulation is a trace of the key variables controlling the work flow over the life of the project. An example of the kinds of results available from a complete model is presented in Figure 6 in the form of the three curves:

(1) Curve A contains the original project cost assuming no intervention;

(2) Curve B provides the project cost estimated at the time a backfit is imposed; and,

(3) Curve C is the actual project costs of the project at its conclusion which includes the backfit costs.

The results of Curve A presents the project manager's expectation for the project expenditures assuming there is no change to the project. This curve is actually generated by the model's planning and scheduling module which emulates a network/critical path planning system. The model evaluates resource constraints assumed at the project outset and developed over the project, monitors the total magnitude of work (including some unavoidable rework), and calculates the overall expenditure rate on the project at various points in time.

For the first analysis, the original project workscope is subjected to a low level of changing requirements introduced at a rate comparable to that experienced by

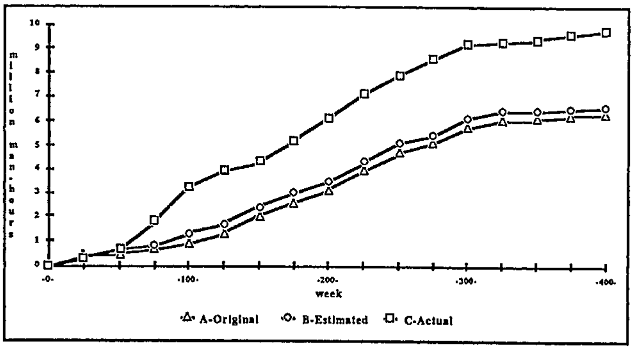

Figure 6

the industry during the previous five year historical period. These requirements are imposed over a 50-week period. As the requirements are identified, the planning module within the project model translates changing regulatory requirements into additional workscope representing the anticipated or "first-order" impacts of regulatory change. The completion of this workscope is planned by the project model so as to optimize the project's scheduled completion date. The model calculates the project expenditure rate as provided in Curve B.

The actual costs of the project - including both direct impacts and indirect ripple effects - are shown in Curve C. As with the other curves, Curve C is a calculated product of the project model. Unlike Curves A and B, however, Curve C is not calculated by the critical path module. Instead, it represents the total cost incurred by the engineers in performing the work under varying conditions of productivity, slack, and rework that are created by regulatory change.

The key feature of Figure 6 is its illustration of the ripple effect. Note the incremental cost of the backfit over the original workscope (represented by the difference between Curve A and B). These curves are the original estimates of the additional charges associated with the backfit. Curve C illustrates ripple effects associated with imposing the backfit on the engineering project. When the project is completed, the ripple effects are over five times what was originally estimated to be added to the project. Moreover, sensitivity analyses not presented here demonstrates that these effects are inherent in any project subjected to external intervention and will resist remedial management policies or procedures.

By utilizing an LPS model, Devonrue was able to accurately assess the impacts of changing government regulations in construction projects at nuclear power facilities. These analyses have conclusively shown, in terms of project cost, completion time, and functional efficiency, that overruns were not only a function of additional design and construction time but they were also caused by "hidden delays" due to incomplete designs being issued late and significant amounts of engineering and construction rework.

LPS MODEL IMPLEMENTATION

Because of their dynamic nature, a dynamic simulation language is required to build LPS models. For construction claim models which are built primarly to develop and strength the arguments of experts involved in the claim, the use of these models is generally restricted to very few simulation runs and the interpretation of the result of the runs is a joint effort of the model builder and the expert which, in some cases, is the same individual. For the development of this type of models, DYNAMO (and Professional DYNAMO for the microcomputer) has been widely used. DYNAMO has the advantage of providing the model builder with an effective tool to build prototypes in a short period of time.

Simulation run times vary of course with the size of the model. For the example discussed above, the model consisted of over 2,000 lines of code containing over 400 variables. The simulation was run over a 400 week time period with one week time steps. Runing time on a VAX 785 was typically 2-3 minutes after compilation. The method of integration was Euler's method. Runge-Kutta were available in DYNAMO but were not required for this simulation.

For other LPS applications such as project management analysis, DYNAMO is not the best suited simulation language. By the nature of the project management analysis models, it can be expected that: (a) these models will have a heavier utilization than construction claim models, and (b) a large number of users will utilize the model. For this application, the desired simulation language is one that enable the modeler to build dynamic model of the problem being analyzed, and that also supports the development of a user friendly interfaces. A third requirement is to effectively support large scale data bases which are an essential component of a large scale construction model.

While a number of dynamic simulation software packages currently exist that can support some aspects of LPS modeling, none completely satisfy all the requirements outlined above. For this reason, C presently is being used as the primary language for building project management analysis models.

Building LPS models using C has the primary advantage of model transportability from microcomputers to mainframes and viceversa. Another advantage is the considerable collection of efficient and inexpensive graphics, windows, and utility programs that interface with C, which give the model greater flexibility in model design. But this flexibility obviously comes at the expense of the additional manpower required for model development.

Clearly a simulation language based on a modern language like C which can handle equally well large scale dynamic models with several hundred state variables, large data bases and user friendly man-machine interfaces could be highly desirable. GSL II is a discrete/dynamic simulation language being currently developed that meet the majority of the requirements for the development of large scale project simulation problems outlined above.

REFERENCES:

DYNAMO and Professional DYNAMO are products of Pugh-Roberts Associates, Inc.

Golden, D., Bradshaw, F., and Huerta, J.(1986). GSLII Design Specifications. Internal document, PDMI, 1986

Huot, J.C. and Cooper, K.G.(1982).Large Project Dynamics. In: *Transactions of the American Association of Cost Engineers,* Houston, Texas, 1982

Huot, J.C.(1986). The Dynamics of Major Projects. In: *Proceedings of the 18th Annual Seminar/Symposium of the Project Management Institute,* Montreal, Canada, 1986

Klinger, A.R.(1966).Bias in Pert Project Completion Time Calculations for a Real Network. *Management Science* Vol. 13, No. 4, December 1966

Schonberger, R.J.(1981).Why Projects are "Always" Late: A Rational Based on Manual Simulation of a PERT/CPM Network. *Interfaces,* Vol.11, No. 5, October 1981

AUTHOR'S BIOGRAPHIES

CHARLES S. ONDASH, ESQ. is a Director at Devonrue. Mr. Ondash has extensive experience in the managerial aspects of large-scale engineering projects. He is one of the developers of LPS at Devonrue. His formal education includes a Bachelor of Science in Electrical Engineering from the University of Dayton, a Master of Science degree in Nuclear Engineering from the University of Wisconsin, and a Juris Doctor degree from Suffolk University.

Devonrue
180 Lincoln Street
Boston, MA 02111
(617) 426-4550

STEPHEN MALONEY, P.E. is a Director at Devonrue. He has more than 15 years experience in engineering and dynamic simulation models for the analysis of large scale problems including the construction of nuclear power plants. He is one of the developers of LPS and has applied it in support of construction claims. Mr. Maloney's formal academic training includes Bachelor of Science degrees in Physics and Mathematics from the Polytechnic Institute of Brooklyn, a Master of Science degree in Operations Research from Northeastern University, and graduate studies in Computer Engineering at the University of Massachusetts. Mr. Maloney is also a registered Professional Engineer.

Devonrue
180 Lincoln Street
Boston, MA 02111
(617) 426-4550

JUAN M. HUERTA, PHD. has over 18 years experience in the analysis of large-scale, complex problems in management and engineering, utilizing techniques in systems engineering, operations research, and computer technology. His formal education includes a Bachelor of Science in Electrical Engineering from the Universidad Iberoamericana, Mexico, a Master of Science in Systems Engineering from Rensselaer Polytechnic Institute, and a Doctor of Philosophy in Electrical Engineering from Cleveland State University.