System Dynamics Modeling for Project Management

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I. System Dynamics Models for Project Management

Project management is at once one of the most important and most poorly understood areas of management. Delays and cost overruns are the rule rather than the exception in construction, defense, power generation, aerospace, product development, software, and other areas. Project management suffers from numerous problems of costing and scheduling. Cost overruns of 100 to 200% are common. Projects are often delayed to the point where the market conditions for which they were designed have changed. Many projects suffer from the "90% syndrome" in which a project is thought to be 90% complete for half the total time required. Project management is often counterintuitive. For example, software development often suffers from Brooks' Law, which states "adding resources to a late project makes it even later". Customer design changes are frequent, generating costly ripple effects which create delay and disruption throughout an entire organization. Projects often appear to be going smoothly until near the end, when errors made earlier are discovered, necessitating costly rework, expediting, overtime, hiring, schedule slippage, or reductions in project scope or quality. The consequences of these difficulties include poor profitability, loss of market share and reputation, increased turnover of management and work force, lower productivity, higher costs, and, all too frequently, divisive and costly litigation between customers and contractors over responsibility for overruns and delays.

This paper describes in brief the use of system dynamics modeling for management of large scale projects, including large scale engineering and construction projects. System dynamics has repeatedly been demonstrated to be an effective analytical tool in a wide variety of situations, both academic and practical, and is currently being used by a number of corporations, including Fortune 500 firms, both in the United States and worldwide. Many of the applications of system dynamics, in both academic research and consulting, involve the quantitative assessment of the costs and benefits of various programs, both retrospectively and prospectively. System dynamics models are widely used in project management, including large scale projects in shipbuilding, defense, aerospace, civil construction, and power plants.[1] System dynamics models are widely used as well in management of software development.[2] The models have been used to manage projects more effectively and to assess the magnitude and sources of cost and schedule overruns in the context of litigation. In addition to project management, system dynamics models are widely used in business strategy and policy assessment. For example, the US. Department of Energy has used system dynamics models of the domestic and international energy system to produce detailed forecasts and policy analysis of energy policies since 1978. Many electric utilities use system dynamics models to analyze policy options for capacity expansion, conservation, pricing, and regulatory changes.[3] The following sections highlight the major issues regarding modeling of project dynamics and provide selected references to the academic and professional literature.

II. Why use computer modeling?

Why should a formal modeling tool be used in project management? And when should formal models be preferred to mental models? Mental models have some powerful advantages. The mental model is flexible. It can take a wide range of information into account, and can process information which is presented in a variety of forms. It can be adapted to new situations and modified as new information becomes available.

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1 See Cooper, K. (1980) Naval Ship Procurement: A Claim Settled and a Framework Built. Interfaces, 10(6), 20-36; Reichelt, K. and J. Sterman (1990). Halter Marine: A Case Study in the Dangers of Litigation. Case Study available from John Sterman, MIT Sloan School of Management, Cambridge MA 02139. See also Roberts, E. (1978) Managerial Applications of System Dynamics. Cambridge, MA: Productivity Press.

2 Abdel-Hamid, T. and S. Madnick (1991) Software Project Management: An Integrated Approach. New York: Prentice Hall.

3 See e.g. "Long Range Energy Projections to 2010," Office of Policy, Planning, and Analysis, US Department of Energy, DOE/PE-0082, July 1988; R. Naill, *Managing the Energy Transition,* Cambridge: Ballinger, 1977; J. Homer, "A Diffusion Model with Application to Evolving Medical Technologies," *Technological Forecasting and Social Change,* 31(3), 1987, 197-218; A Ford et al., "Bonneville's Conservation Policy Analysis Models," *Energy Policy,* 15(2), 1987, 109-124; J. Sterman, G. Richardson, P. Davidsen, "Modeling the Estimation of Petroleum Resources in the United States," *Technological Forecasting and Social Change.* 33(3), 1988, 219-249. While many of the successful corporate applications of system dynamics are proprietary, a sense for the scope and use of the technique can be gleaned from published articles in the *System Dynamics Review* and other journals in the management and social sciences and from the proceedings of the annual international system dynamics conferences (available from System Dynamics Group, E40-294, MIT Cambridge MA 02139).

But mental models also suffer from great disadvantages. Mental models are not explicit. They are not easily examined by others. Their assumptions are hard to pin down in debate or discussion. Interpretations differ. Ambiguities and contradictions can go unresolved.

Of more concern is the fact that people do a poor job of interpreting the assumptions of their own mental models. Wondrous as it is, the capability of the human mind is bounded by various limitations of attention, memory, and information processing capability. Individual perspectives may be parochial, information incomplete, dated, or biased, and the time available to weigh alternatives insufficient. People, even experts, have great difficulty inferring accurately the behavior of complex dynamic systems.[4] Professor Herbert Simon of Carnegie-Mellon University, winner of the 1978 Nobel Prize in Economics, has summarized the situation in his famous "principle of bounded rationality":

> The capacity of the human mind for formulating and solving complex problems is very small compared with the size of the problem whose solution is required for objectively rational behavior in the real world or even for a reasonable approximation to such objective rationality.[5]

In practice, the bounded rationality of human judgment means that the best-intentioned mental analysis of a problem as complex as a large construction project cannot hope to account accurately for the myriad interactions which jointly determine the outcome of the program. No mental model can adequately assess the impact of externally imposed changes or allocate responsibility for delay and disruption.

Computer models help overcome many of the limitations of mental models because they:

- are explicit, and their assumptions are open to all for review;

4 The literature is massive. A readable introduction is provided by R. M. Hogarth, *Judgement and Choice*. New York: Wiley, 1980. See also A. Tversky and D. Kahneman, "Judgment Under Uncertainty: Heuristics and Biases," *Science*, 185 (27 September 1974), 1124-1131; for a comprehensive treatment see D. Kahneman, P. Slovic, and A. Tversky, *Judgment Under Uncertainty: Heuristics and Biases*, Cambridge: Cambridge University Press, 1982.

5 H. Simon, *Models of Man*. New York: Wiley, 1957, p. 198.

- infallibly compute the logical consequences of the modeler's assumptions;
- are able to interrelate many factors simultaneously;
- can be simulated under controlled conditions, allowing analysts to conduct experiments which are not feasible or ethical in the real system.

These advantages do not mean that computer models are always superior to mental models. As with any tool, computer models can be misused. Examples of good and bad practice may be found. The characteristics of formal models cited above, however, often make it easier to assess the quality and validity of formal models compared to mental models.

III. Models for Project Management

Large scale projects belong to the class of complex dynamic systems. Such systems:

1. are extremely complex, consisting of multiple interdependent components;
2. are highly dynamic;
3. involve multiple feedback processes;
4. involve nonlinear relationships;
5. involve both "hard" and "soft" data.

To manage such complexity properly, a model must be capable of representing systems with these characteristics, and it must be understandable and usable by the managers of the projects. The following sections describe these characteristics in more detail.

III.1 Construction projects are extremely complex, consisting of multiple interdependent components

Interdependencies complicate analysis beyond the capabilities of mental models because a change in one part of the system may have implications in other, remote parts. In contrast to much of daily experience, cause and effect in such systems are not closely related in time and space. For example, changing the location of a fitting in an engineering drawing may cause subsequent changes in other subsystems such as electrical, HVAC, etc., necessitating rework far beyond the original change. These changes may in turn cause workers to be rescheduled from one task to another, delaying some tasks and accelerating others. Such juggling of resources to handle the rework may then lead to delays on other projects which find themselves dependent on completion of the deferred tasks. Such systems are termed "tightly coupled" in systems engineering and are notorious for their counterintuitive character.[6] Effective understanding of such systems almost always involves the use of formal models. System dynamics models are well suited to representing such multiple interdependencies. Indeed, one of the chief uses of system dynamics is to capture such interdependencies so that the causal impact of changes may be traced throughout the system.

III.2 Construction projects are highly dynamic.

Project management is intrinsically dynamic. Processes such as hiring and training unfold over time. There are multiple time delays in carrying out programs, in discovering and correcting errors, and in responding to unexpected changes in project scope or specifications. Such dynamic elements mean that the short run response of a system to a perturbation may differ from the long run response. For example, hiring additional workers adds to the capability of an organization in the long run, but in the short run, experienced workers must divert time from their work to train the recruits, reducing productivity. System dynamics was developed to deal with exactly such

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6 See e.g. Charles Perrow, *Normal Accidents: Living with High Risk Technologies.* New York: Basic Books, 1984.

dynamics. Of all the formal modeling techniques, system dynamics has the most highly evolved guidelines for the proper representation, analysis, and explanation of the dynamics of complex technical and managerial systems.

III.3 Construction projects involve multiple feedback processes

A complex system such as a large scale construction project contains multiple interacting feedback processes. Feedback refers to the self-correcting or self-reinforcing side effects of decisions. For example, when a project falls behind schedule, one possible managerial response is to increase the use of overtime. The extra hours help bring the project back on schedule, reducing the need for overtime in the future. Such a feedback process is self-correcting. However, if overtime remains high for an extended period, workers may become fatigued and burned out, leading to lower productivity, a higher rate of errors, and increased employee turnover, thus further delaying the project and leading to pressure for still more overtime, in a vicious cycle or self-reinforcing feedback process. Tightly coupled systems such as a construction project contain large numbers of important feedback relationships. Feedback processes are fundamental to the dynamics of managerial, technical, and other systems. System dynamics is the modeling method of choice whenever there are significant feedback processes.[7]

Mental models and traditional cost and scheduling tools such as critical path methods do not adequately account for feedback effects. People are notoriously poor judges of feedback and causality, and in controlled experiments have repeatedly been shown to misperceive the feedback structure of systems much simpler than a large engineering or construction project.[8] Experts are not immune from these errors.[9] Though very helpful to schedule the sequence of activities in a

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7 See G. Richardson, *Feedback Thought in Social Science and Systems Theory.* Philadelphia: University of Pennsylvania Press, 1991.

8 J. Sterman, "Misperceptions of Feedback in Dynamic Decision Making," *Organizational Behavior and Human Decision Processes.* April 1989, 43(2), and J. Sterman, "Modeling Managerial Behavior: Misperceptions of Feedback in a Dynamic Decision Making Experiment," *Management Science.* March 1989, 35(3).

9 E.g. Kahneman, Slovic, and Tversky, op. cit.; J. S. Armstrong, *Long Range Forecasting: From Crystal Ball*

project, tools such as Gantt charts, PERT and critical path methods do not solve the problem. A critical path analysis determines how a change in the time required to complete one step such as an engineering drawing may affect the total completion time for a project. However, the time required for each individual step is estimated by the analyst on the basis of historic data, past experience, or judgment. If customer requirements were to change, or errors necessitating rework were discovered after the project has begun, the analyst can re-estimate the schedule by changing the time required for the small number of individual steps directly affected by the change and then recompute the critical path and time required for completion. The implicit assumption is that the time required to carry out all other steps is unaffected. That is, all other interactions are ignored.

But interactions abound. For example, a change in customer specifications for a subsystem and subsequent issue of engineering change order may require the hiring and training of additional engineers, which in turn diverts skilled engineers from design work to training. Trainees may generate more errors, increasing rework. Engineering changes render other, previously completed drawings obsolete and may also make some construction work already begun obsolete. Purchase orders already issued may have to be revised; some subcontracted components in process must be reworked. Additional design and construction work must now be done without firm knowledge of how related components and subsystems will interact, leading to still more rework. Additional hiring can lead to congestion in the shop and at the construction site, lowering productivity, increasing errors, and possibly leading to safety incidents. As these effects accumulate, the project management team has less and less time to oversee other aspects of the program, so quality and timeliness can suffer in areas previously doing well. Customer relations can deteriorate, and meetings, reviews, and customer oversight can grow increasingly burdensome.

In this fashion the impact of the original change ripples through the entire organization, slowing progress, reducing productivity, and raising costs at every stage in the project. If the changes are

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to Computer, New York: Wiley, 1985 (2nd ed.).

large enough, the ripple effects create schedule compression and increase the degree of concurrency in design and between design and construction, resulting in excessive overtime, fatigue, increased errors, reduced quality, and strains on the project management team such that the actual cost of a seemingly innocent design change can exceed by many times the direct cost of the change order itself. Unless a project manager or scheduling analyst anticipates all these feedbacks and interactions and manually inserts the changes, the critical path method will tend to underestimate the impact of the changes, often dramatically.

The preceding discussion, however, does not imply that traditional costing and scheduling tools such as PERT are unimportant. System dynamics should be seen as complementary to traditional scheduling and project management tools: where traditional tools are useful to deal with the *combinatorial complexity* of complex projects with multiple parallel and sequential activities, system dynamics is useful to deal with the *dynamic complexity* created by the interdependencies, feedbacks, time delays, and nonlinearities in large scale projects.

III.4 Construction projects involve nonlinear relationships

Nonlinear relationships are the norm rather than the exception in complex systems. Nonlinearity means causes and effects do not have simple, proportional relationships. For example, consider the relationship between workweek and productivity discussed above. Increasing the workweek for engineers from 40 to 44 hours per week may increase drawing output by 10 per cent (4/40). But additional overtime may rapidly lead to diminishing or even negative returns as longer hours cause fatigue, additional errors, and other effects which were previously unimportant. System dynamics models portray the rich range of nonlinear relationships found in real life with great fidelity. System dynamics, more than any other formal modeling technique, stresses the importance of nonlinearities in model formulation.[10]

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[10] See G. Richardson and A. Pugh, *Introduction to System Dynamics Modeling with DYNAMO*, Cambridge: The MIT Press, 1981; J. W. Forrester, "Nonlinearity in High-Order Models of Social Systems," *European Journal of Operational Research*, 30 (1987).

III.5 Construction projects involve both "hard" and "soft" data

A large scale construction project is not merely a matter of engineering – of drawings, steel, pipes, and wiring. It is essentially a human enterprise, and cannot be understood solely in terms of technical relations among components. Some, perhaps most, of the important data needed to understand the evolution and dynamics of such a project will concern managerial decision making and other so-called "soft" variables.

The overwhelming majority of all data are descriptive and qualitative. And the majority of these data have never been written down. Yet they are crucial for understanding and modeling complex systems. Imagine trying to operate a school, factory, or economy solely on the basis of the available numerical information. Without the descriptive knowledge of operating procedures, organizational structure, and so on, the result would be chaos. System dynamics practitioners and theorists recognize the importance of such so-called soft data. System dynamicists are taught to use multiple sources of information, including numerical data, interviews, direct observation, and other techniques to elicit the decision rules, organizational structures, goals, and other important managerial dimensions of the system. The skilled modeler uses all available information sources to specify the relationships in the model.

IV. Validation of Simulation Models

System dynamics has developed an extensive literature on the validation of simulation models.[11] The literature emphasizes that historical fit, the ability of a model to replicate the past behavior of a system, is but one of many tests to which a model must be subjected. System dynamics practitioners emphasize the use of a variety of tests in addition to historical fit. These tests focus on the correspondence of the model structure to the system, the robustness of the model's behavior, and the robustness of policy recommendations. The process of model validation is largely one of opening the model to scrutiny and test by the management team. The focus of validation is interactive testing of critical modeling assumptions. The model becomes a participant in the dialogue about project management.

V. Client Involvement

Traditionally, formal modeling tools were complex and inaccessible to all but the trained analyst. As a result, models were developed by experts without direct involvement in the modeling process by the managers who were expected to use the results of the models. The inability of the managers to participate in the process created a dilemma. If the modelers built a simple model, they were criticized for ignoring important relationships. If they built a complex model, they were criticized for creating a black box no one could understand. Often, both criticisms are leveled at the same time: 'your model is oversimplified *and* too hard to understand'. Black box modeling short-circuits the process of learning through which people come to improved understanding of complexity. Without improved understanding, the likelihood of successful *sustainable* organizational change is small.

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[11] For example, J. Forrester and P. Senge, "Test for Building Confidence in System Dynamics Models," *TIMS Studies in the Management Sciences*, 14, 1980, 201-228; Richardson and Pugh, op. cit.; N. Mass and P. Senge, "Alternative Tests for the Selection of Model Variables," *IEEE Transactions on Systems, Man, and Cybernetics*, 8(6), 1978, 450-460; J. Sterman, "Appropriate Summary Statistics for Evaluating the Historical Fit of System Dynamics Models," *Dynamica*. 10(2), 1984, 51-66.

The solution to the dilemma is the intensive involvement of the management team in the modeling process. New software tools now make it possible for managers to participate as full partners in model development. Sophisticated interfaces and intuitive design allow managers and employees throughout a firm to use, test, and revise complex models. This approach has yielded some notable successes. Often, the models are converted into interactive "Management Flight Simulators" which can be disseminated widely throughout the organization. Models have become the basis for "learning laboratories", a process for creating a practice field for managers in which they can learn about the long-term side effects of decisions without risk to the real organization. Such simulators have been successfully used as educational tools and as tools for management of ongoing projects in a wide range of organizations, at all levels of management from the assembly line to the boardroom.[12]

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[12] See:

Senge, P., & Sterman, J. D. (1991). Systems Thinking and Organizational Learning: Acting Locally and Thinking Globally in the Organization of the Future. In Kochan, T. & Useem, M. (Eds.), *Transforming Organizations* Oxford: Oxford University Press;

Graham, A. K., Morecroft, J. D., Senge, P. M., & Sterman, J. D. (1992). Model Supported Case Studies for Management Education. *European Journal of Operational Research*, 59(1), 151-166;

de Geus, A.P., 1988, Planning as Learning, *Harvard Business Review*, March-April, 70-74;

Stata, R., 1989, Organizational Learning -- the Key to Management Innovation, *Sloan Management Review*, 30, 3 (Spring), 63-74.

Sterman, J. D. (1988, *People Express* Management Flight Simulator. Simulation Game (software), Briefing Book, and Simulator Guide, Available from author, MIT Sloan School of Management, Cambridge, MA 02139.