A PROJECT MANAGEMENT CAUSAL LOOP DIAGRAM

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System dynamics principles and analytical tools have the potential to alleviate several deficiencies in current project management analytical techniques. This paper facilitates the integration of system dynamics into project management by providing an overview of system dynamics principles, summarizing the deficiencies in current project management approaches, and presenting a causal loop diagram of a generic project management system. The feedback loops in the diagram explains how what appear to be rational project management actions can lead to unintended and counterintuitive consequences.

Keywords: Project management, system dynamics, causal loop diagrams, feedback loops.

INTRODUCTION

Many large projects do not meet their time and cost goals (Sterman 1992). Moreover, as projects get more complex, as completion time becomes more critical, and as concurrent design and implementation (such as fast-track construction) becomes more prevalent, failure to meet project goals is likely to become increasingly common (Williams 1999). Project manager researchers (Rodrigues and Bowers 1996, Williams 1999, Love et al 2002) have written that one reason project goals are often not met is that the project management concepts and tools used today are too linear and deterministic. The systems in which project management occurs are too complex and volatile and contain too much apparent randomness to be managed effectively by the linear, deterministic tools that focus on one portion of the system at a time. These researchers have suggested that system dynamics concepts and tools, such as causal loop diagrams and detailed models, should be integrated into project management practices to allow project managers to better understand the structure of the system in which project management occurs and consequently better plan and control projects.

The integration of system dynamics into project management has not yet happened. This paper attempts to facilitate this integration by presenting a causal loop diagram of a generic project management system that builds on existing literature to illustrate the insights that system dynamics provides. It is intended that the paper be of interest to all project management researchers, not just those interested in construction projects or system dynamics. The examples used throughout the paper are from construction project management, but the concepts and classification schemes apply to all projects.

The structure of the paper is as follows. The paper first summarizes system dynamics principles and tools and the criticisms of project management tools made by system dynamic researchers. After briefly examining the limited effort made to integrate

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project management and system dynamics to date, a project management causal loop diagram is presented. The paper concludes by examining the implications for project managers of multiple feedback loops within project management systems.

FUNDAMENTALS OF SYSTEMS THINKING AND SYSTEM DYNAMICS

System dynamics is both a methodological approach and set of tools based on systems thinking. System dynamics was originated by Prof. Jay Forrester at MIT and has slowly spread to other universities and into industry. Initially used to model electro-mechanical processes, system dynamics has been used extensively to model organizational, social, economic, biological and other types of systems.

Fundamental systems thinking and system dynamics concepts, assumptions, and tools summarized from (Forrester 1961, 1971; Richardson 1986; Senge 1990; Sterman 2000) are listed below.

- Systems can be defined simply as a collection of connected things, that is, a set of elements that influence one another.

- The things may be easily quantifiable, such as the revenues of a firm, or more intangible and qualitative, such as goodwill, motivation, and burnout.

- The structure of a system reflects how many of the elements can accumulate (as opposed to being more ephemeral) and how the accumulating elements influence one another.

- Much of the system structure and the underlying relationships can be depicted graphically using causal loop diagrams. To create a causal loop diagram, one needs to identify the variables associated with a system, identify which of these variables are causally related to other variables within the system, and decide whether the effect of one variable on another is positive or negative. A plus sign indicates that when the variable next to the tail of an arrow increases, the variable next to the head of the arrow also increases. A minus sign indicates that when one variable increases, the other variable decreases. For example, Figure 1 depicts a portion of a simple project management system. If the actual rate at which a task is accomplished—task productivity—decreases, schedule variance will increase. Schedule variance will cause the project manager to direct that overtime occurs, which will increase the rate of task accomplishment and reduce schedule variance.
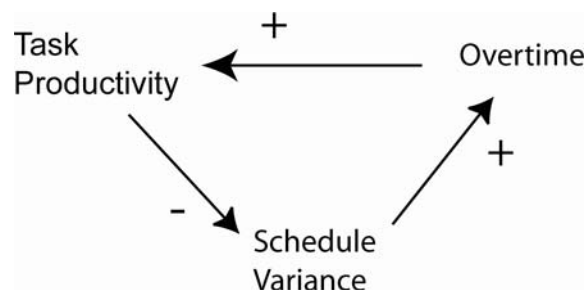

Figure 1: A simple project management feedback loop

- A key benefit of creating causal loop diagrams is that individual mental models can be elicited and compared. People often incorrectly assume that every one shares their understanding of how one thing affects another. When people

disagree on how a specific problem should be resolved, it is often because they share different mental models of the system in which the problem is embedded.

- Portions of the structure of a system may include feedback loops, that is, element A affects element B which affects element C which affects element A. The causality around the loop typically occurs over time, that is, a change in element A takes several iterations to cause changes in the other variables within the feedback loop. Feedback loops can be positive or negative. Positive loops are self-reinforcing; that is, variables within positive loops will continue to increase indefinitely. Negative loops are self-balancing; that is, variables within negative loops will stabilize over time. One can usually identify the polarity of a feedback loop (i.e., positive or negative) by summing the polarities of the individual relationships between the variables within the loop. Loops with an odd number of negative relationships will generally be negative. Loops with an even number of negative relationships will generally be positive. Figure 1 is an example of a negative loop because it has one negative relationship in it.

- The pattern of changes in the values of variables within a simple system over time (i.e., the shapes of plots of the variables) can often be predicted based on the structure of the system, specifically, the number of accumulating variables within feedback loops and the polarity of the feedback loops.

- The values of variables within more complex systems—that is, systems that include many accumulating variables and more than one feedback loop—may not be easily predictable. In fact, the patterns may be highly counterintuitive.

- Because behaviour of variables within a complex system may be counterintuitive, observers may assume that a system is being affected by exogenous factors. In reality, a system's behaviour may reflect actions occurring within the system (often by the observer) that are compounded by the structure (i.e., interrelationships) of the system.

SYSTEMS DYNAMICS APPLIED TO PROJECT MANAGEMENT

Network analysis tools allow the user to calculate the expected completion dates of individual tasks and the overall project based on deterministic estimates of individual task durations and the sequencing of the tasks. These tools facilitate important analysis, such as the effect on successor tasks and the project if the completion of a task is delayed, or how the usage of individual resources can be levelled to prevent delays and minimize costs. These tools therefore help project managers plan and control for achieving project goals relating to completion time and costs.

Yet these tools suffer from several critical deficiencies which limit the power of project management tools to help plan and control a project's schedule and cost. One deficiency is that the estimates of individual task durations and costs are typically based on historical data and assumed to be deterministic; that is, project managers estimate one expected value for the duration, not a mean and two extreme values as is the case with PERT analysis. Network analysis provides no quantitative indication of the likelihood that the estimated task durations and costs will be achieved.

Completing each task on time and within budget is the essence of project management. Project managers deploy resources to accomplish these tasks as efficiently as possible. Stated differently, project managers manage cause and effect relationships to meet their goals. If a task is behind schedule, they *cause* more

resources to be deployed, thereby *effect*ing an earlier completion than if they had not increased the resources deployed. However, the cause and effect relationship in this situation is more complicated than is assumed by the use of network analysis tools (Sterman 1992, Rodrigues and Bowers 1996, Pena-Mora and Parks 2001).

Consider, for example, a task with an original planned duration of twelve days assuming a four-person crew working eight hours per day. If it was necessary to reduce this duration by four days down to eight days, one might assume that it would be necessary merely to require the four-person crew to work twelve-hour days. It is unlikely, however, that increasing resources will result in a proportional reduction in duration. Requiring substantial overtime will fatigue the workers, which will result in decreased productivity, which will result in a non-linear reduction in task duration. Similarly, fatigue may result in poor quality, which will necessitate rework, which will also result in a non-linear reduction in task duration. In short, the task would likely not be completed in eight days as assumed.

Figure 2 is a causal loop diagram showing the variables mentioned above. The reader may note that the longer feedback loop (around the entire perimeter) includes an even number of negative causal relationship and is therefore a positive, i.e., self-reinforcing, feedback loop. If the positive feedback loop dominates the negative feedback loop, requiring overtime might therefore result in increased schedule variance, not decreased variance as intended. This simple example indicates that taking a system dynamics approach reveals that a decision to crash a task based solely on linear assumptions would ignore several important aspects of the underlying project system and result in a less than ideal decision.
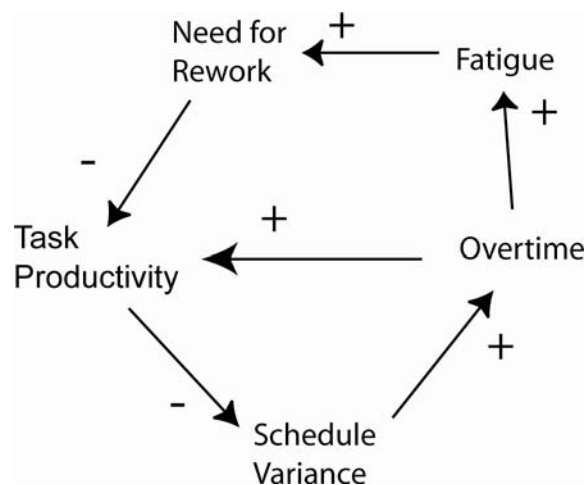

Figure 2: An unintended project management feedback loop

Examples such as this have been used to suggest that construction and other dynamic projects would be better managed by applying system dynamics concepts and tools (Pena-Mora and Park 2001, Rodrigues 2001, Love et al 2002). Sterman (1992) provides broad but powerful insights into why large complex projects require the unique conceptual approaches and analytical tools provided by system dynamics. As noted by Rodrigues and Bowers (1996), the application of system dynamics to project management has been motivated by four primary goals:

- the need to take holistic approach (recognizing that the whole is greater than sum of the parts);
- the need to understand non-linear behaviour;

- the need for a learning laboratory tool; and

- the desire to try new, potentially more effective techniques.

System dynamics models have been applied to project management topics in the past. Rodrigues and Bowers (1996) included an extensive list of articles, most of which are associated with R&D or software development projects. More recently, Pena-Mora and Park (2001) used causal loop diagrams and a detailed computer model to model the effect of concurrent design and construction (fast-tracking) on building completion time and cost. Love et al (2002) used causal loop diagrams to gain insight into the effect of scope changes on construction projects. (Gelbard et al (2002) discussed the integration of systems analysis computer tools and project management tools, but systems analysis tools were not based on system dynamics. Ogunlana et al (2003) created a systems dynamics model of a construction company, but the model focused on the management of the company, not on individual projects. Park, Nepal and Dulaimi (2004) used system dynamics to model construction innovation on a project level.

The discussion above has indicated that network tools are of limited value in managing project duration and cost. Perhaps just as important is that these tools are of no help in managing two other key project goals: quality and safety. Quality can be defined on the most basic level as meeting customers' expectations for functionality and appearance. Safety can be defined on the most basic level as having no temporary or permanent reduction in the health of the personnel executing the project. Project management has become more challenging in recent decades because clients are not only demanding shortest possible completion times but also paying more attention to quality and safety than ever before. Many project managers believe that in most project management contexts, the four project goals—time, cost, quality and safety— are at least somewhat in competition with one another. Excessive emphasis on timely completion, for example, will make it more difficult to achieve project goals in cost, quality and safety. If this is even partially true, project management tools that ignore quality and safety are clearly unsatisfactory.

It is this author's opinion that applying system dynamics to project management has not achieved its potential, particularly for construction projects, because academics and practitioners have not been sufficiently exposed to useful project management models and causal loop diagrams. There has been no published *model* of a generic project management system to provide sufficient insights into the complex systems that underlie project management. Consequently, researchers and practitioners have not had a generic project management model that they could modify for their own learning laboratory purposes.

The project management *causal loop diagrams* (CLD) published to date have not been complete; that is, they have not encompassed the entire system underlying the management of a project. A CLD that is intended to be a more complete diagram is presented in the following section.

A PROJECT MANAGEMENT CAUSAL LOOP DIAGRAM

This section of the paper presents a CLD for a generic project management system. While it is believed that the diagram is more complete than found in previous literature, it is not represented as including all variables for all project management contexts. The intent is to include a sufficient number of key variables and their relationships to represent reality, without including so many variables that model users

are overwhelmed. For example, rather than modeling the individual productivity, cost, safety and quality of each task, these variables are aggregated into project-level variables in the model. Similarly, the competences, goodwill and workload of all assistant project managers (APMs) are aggregated into three project-level variables. The CLD presented here is also not represented as accurately depicting the system underlying all project contexts. Instead, this CLD is intended to serve as a generic Straw Man that project managers can discuss to create customized CLDs that best represent their own project management systems.

The CLD (see Figure 3) includes several important groups of variables connected by key causal relationships. The most important variable in the model is Task Productivity, which represents how fast tasks are performed. One variable that affects Task Productivity is APM Productivity, which reflects the three characteristics of APMs mentioned in the preceding paragraph: workload, competence and goodwill. The latter variable refers to the APMs' morale or motivation level. The principles or assumptions underlying these relationships are that project management personnel can substantially influence each task's progress, and that less competent, overworked, or demoralized project management personnel can cause progress to be slower than originally estimated.

Another key group of variables includes the variances associated with four project goals: schedule, cost, quality and safety. Variances occur when actual project characteristics are less than the planned characteristics at a specific point in time. For example, schedule variance means the project is behind schedule, cost variance means the project is over budget, quality variance means that rework is necessary, and safety variance means that site injuries are more likely to happen.

Another group of variables include the project manager's emphases on the four areas of project goals. The arrows between these variables reflect the assumption that while project managers may have specific goals in all four areas, it is the relative emphases between the goals that is important. In other words, a project manager cannot effectively emphasize all criteria; project personnel will focus on the area or areas that their supervisor emphasizes the most.

Overtime and Fatigue are another set of important variables due to their assumed effects on variances. If schedule variance occurs, project managers will typically attempt to get back on schedule by directing overtime, which leads to cost variance. (Increasing crew size is sometimes an alternative solution, but was omitted from the CLD to prevent unnecessary complexity.) Overtime often leads to worker fatigue, which can lead to quality and safety variance and reduce worker productivity.

The final set of variables includes the goodwill of the project manager's Boss and the project Client. Goodwill for these variables refers to the degree of satisfaction with the project manager. Client goodwill is important because it will influence whether he or she contracts again with the project manager's company. Boss goodwill is important because it will influence promotion and financial rewards. Boss goodwill is assumed to influence APM workload because "keeping the bosses happy" is often one of the top informal goals of project management personnel. Consequently, if Boss goodwill drops, APMs will have to work harder to restore a good relationship.
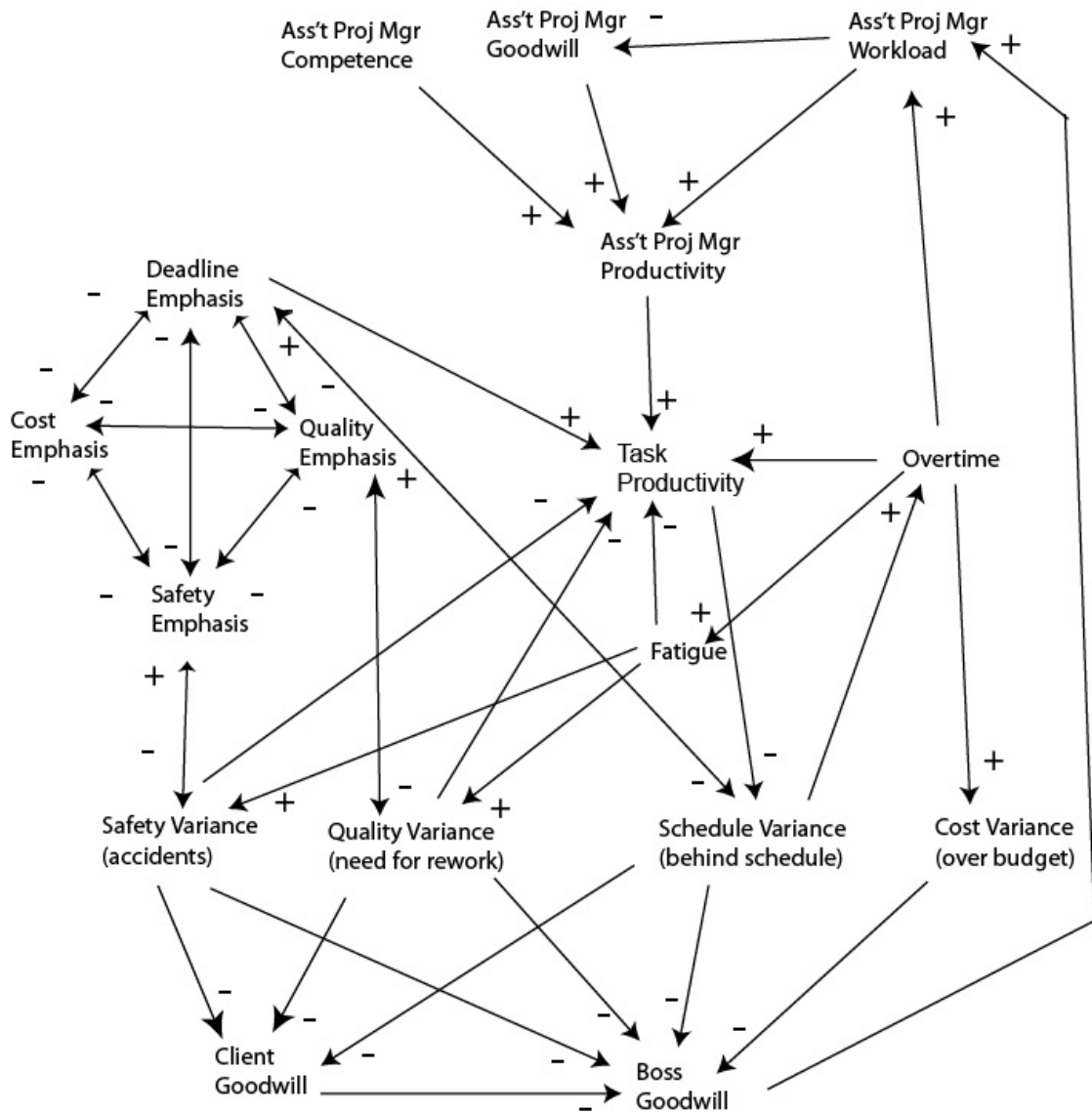
Figure 3: A more complete project management causal loop diagram

The fact that Figure 3 does not include all variables underlying a project management system, acknowledged earlier, warrants further discussion. For example, task productivity is certainly affected by variables that are not shown in Figure 3, such as characteristics of the construction site, the weather, the building being constructed, and the crew performing the task. Schedule variance results not just from lower than expected task productivity, but also from scope changes, unforeseen conditions and deficiencies in the design documents. Quality and safety variances result not just from fatigue and the relative emphases on these goals, but also on the quality and safety management systems within the subcontractor's, general contractor's and owner's organizations. These variables have been intentionally omitted from Figure 3 because the goal of the CLD is not to provide a diagram for rigorous quantitative analysis, such as structural equation modeling. Rather, the intention is to provide a diagram that depicts the feedback loops within the system because it is the loops that can lead to counterintuitive behaviour. Variables that are not part of feedback loops are therefore not as important for understanding system behaviour and are omitted to keep the model from being needlessly complicated.

The CLD features a number of important feedback loops, which substantially influence the behaviour of the system. There is one key negative feedback loop, which was previously discussed for Figure 1: Task Productivity - Schedule Variance - Overtime - Task Productivity. This loop reflects the assumption that if a task falls behind schedule, project management will direct workers to work overtime to put the task back on schedule in order to meet project deadlines.

There are at least ten positive feedback loops in the system, which make the entire system somewhat volatile. As mentioned earlier, positive feedback loops are self-reinforcing, which means they can rapidly increase or decrease the values of variables within them. Such feedback loops are associated with high potential for either a rapid downward spiral or a rapid upward trend in project performance or both. Task Productivity - Schedule Variance - Boss Goodwill - APM Workload - APM Productivity - Task Productivity is an example of a loop that has both positive and negative potential. If tasks are progressing well, the project can become ahead of schedule, which makes the boss happy and lets the APM focus on improving the progress rate even more. Alternatively, if task progress decreases, overtime becomes necessary, which leads to cost variance, which makes the boss unhappy, which increases the APM's workload, which decreases task progress.

Positive feedback loops that involve inherently negative variables can only result in downward spirals. For example, many of the positive feedback loops in the CLD involve fatigue. Several of these loops were discussed earlier, such as Task Productivity - Schedule Variance – Overtime – Fatigue - Quality Variance (or Safety Variance) - Task Productivity. This loop can be summarized as excessive overtime leads to worker fatigue, which increases the need for rework and the likelihood of accidents, both of which reduce task progress. Another set of fatigue feedback loops involve these same variables but also include client and boss goodwill, such as Task Productivity - Schedule Variance – Overtime – Fatigue - Safety Variance - Boss Goodwill - APM Workload - APM Productivity - Task Productivity. That is, fatigue-induced injuries will make the boss dissatisfied, which leads to APMs working harder, which increases their workloads to the point where task progress is reduced. Fatigue can never be associated with desirable system behaviour because when the project is ahead of schedule, overtime is not necessary so fatigue remains zero and the positive feedback loops involving fatigue do not come into play.

CONCLUSIONS

Despite the need to integrate system dynamics principles and tools into project management as articulated by Rodrigues and Bowers (1996) and the popularity of systems thinking among corporate managers that has been spurred by The Fifth Discipline (Senge 1990), integration of system dynamics into project management has progressed slowly. To encourage this integration of the two fields, this paper has summarized system dynamics principles, presented a causal loop diagram for project management, and used this CLD to discuss the feedback loops that characterize project management systems.

It is not suggested that the CLD presented here accurately depicts all project contexts. It is intended to serve as a straw-man that project management researchers and practitioners can use as a starting point to create a CLD of their own project management system. For example, the CLD presented here includes many feedback loops associated with undesirable consequences of worker fatigue and the workload of

project management personnel becoming excessive. The reader may feel that these variables are not important in their project context and wish to add other variables that are critical for his or her project.

Taking a systems approach and creating a CLD of their project management system has implications for what project managers can and should do. The key tenant of systems thinking is that all elements within a system are related. Project managers that focus solely on meeting deadlines and/or budgets are likely to experience undesirable performance in quality and safety, which will ultimately affect the project completion and cost. Project managers should avoid making sudden and drastic changes in the amount of emphasis placed on any one goal because such changes are likely to lead to undesirable variances associated with other project goals. A systems approach also points at the danger of making decisions based on old information if there is delayed feedback within the system. It is therefore important to establish management information systems and decision making processes to prevent decisions based on outdated or incomplete information.

A CLD allows project managers to better predict potential consequences of their decisions and actions resulting from feedback loops within the project management system. Project managers should study their project CLD to determine whether the system is likely to be dominated by positive or negative feedback loops. A system dominated by negative feedback loops is likely to have a systemic resistance to perturbations within the system, including to management actions taken to improve project outcomes. Implementation of changes in such a system may therefore require introducing change in several locations within the system and using multiple methods.

A system dominated by positive feedback loops, on the other hand, is likely to have a high degree of instability, such that perturbations (such as management actions and exogenous events) can lead quickly to major changes in project performance. Implementation of changes in a positive feedback system therefore warrants a cautious approach that includes monitoring key variables for indications that undesirable positive feedback loops have been activated. For example, introducing change into the system depicted in Figure 3 should be accompanied by frequent monitoring of APM workload and worker fatigue to prevent variances arising in quality and safety. It would also be prudent to build initial slack into key resources associated with positive feedback loops.

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