A Systems Approach to Risk Management

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Abstract: *In today's world, most engineering management projects are extremely complex and are very difficult for any one person or even one organization to fully understand. Consequently, understanding and managing risk becomes increasingly difficult in this environment. The purpose of this study is to examine how systems thinking can help reduce risk in large complex projects. It looks at the problem of risk from a number of perspectives, as both the risk of losing personnel to job hazards, as well as the financial risks involved when projects go over budget and over time. This paper explains how System Dynamics can be used to help model large, complex problems, and how doing so helps us to better understand the internal feedback mechanisms involved in nearly all large systems. It also shows how System Dynamics models can then be simulated to help determine which policy drivers are most important in the system, allowing policy makers to make informed decisions. Finally, it examines two case studies where System Dynamics modeling was used to help manage risk within an organization.*

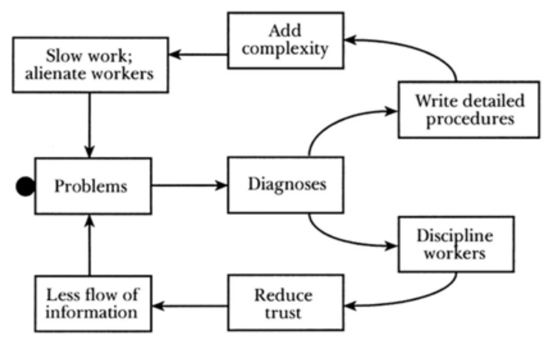
Introduction

Risk Management is an extremely wide field, with applications in virtually every industry imaginable. Consequently, many processes have been created to help mitigate risk, most of which are domain specific. For example, the finance industry created hedge funds to help mitigate risk in investments, and perhaps on the other side of the spectrum the U.S. Army created the Composite Risk Management system to help mitigate fatalities and the loss of valuable equipment to accidents (Department of the Army, 1).

This paper shows how System Dynamics can be applied towards solving risk management problems. Unlike many existing risk management strategies which are typically domain specific, System Dynamics theory can be applied to almost any risk management problem. This is because System Dynamics focuses on modeling the system, identifying the key feedback loops inherit to the system, and examining what policies can be implemented to help mitigate risk in the system. Understanding how feedback affects a system is critical because both "external" and "internal" feedback affects most systems, and it is difficult to see across system boundaries without some form of systems modeling and analysis (Parnell et. al, 2008).

The concept of feedback is not entirely new to the field of risk management. In his study of high-hazard industries, John Carroll notes that most accident investigations produce problem diagnoses that are worker centric, resulting in extensive written detailed procedures and discipline. While these "fixes" were initially well intended, they often lead to added job complexity and a reduction in trust between workers and management, which leads to slower work speed, alienation of workers, and a reduced flow of information between supervisors and their subordinates. As shown in Figure 1, this leads to increased problems and therefore, a cycle of accumulating problems, accidents, and worker resentment (Carroll, 1998).

Figure 1: Unintended Consequences (from Carroll, 1998, p.715)



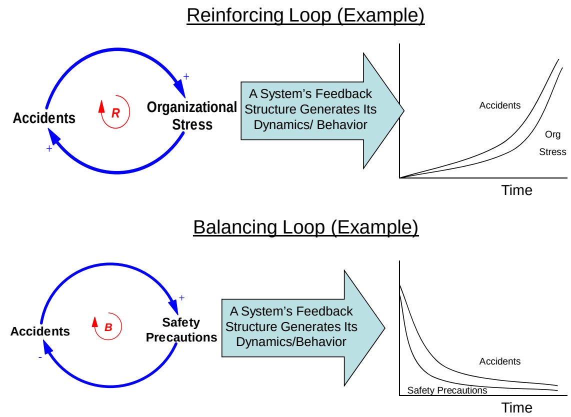
There are several studies where researchers applied System Dynamics modeling techniques to help mitigate risk in various industries. Lyneis and Madnick (2008) developed a model that focused on the effect of task backlog and adherence to rules and procedures and showed that making safety a high priority by limiting production pressure is by far the highest leverage policy available to managers seeking to prevent accidents. Leveson and Cutcher-Gershenfeld (2007) developed a model examining the Space Shuttle Columbia accident and showed how a build-up of success over time led to a growth in complacency, which ultimately played a key role in the shuttle accident. Rudolph and Repenning (2002) developed a model depicting the performance of air traffic controllers and showed how stress has both positive and negative effects on air traffic controller performance. Finally, Oliva and Sterman (2001) developed a model of backlog at a call center and showed how service level declines over time, which produces a reinforcing cycle of lower standards and less capacity.

System Dynamics Theory

System Dynamics was developed during the 1950s by MIT Professor Jay Forrester as a method for modeling large real world systems (Forrestor, 1961). Central to the System Dynamics modeling strategy is the representation of system structure in terms of stocks and flows, which measure the accumulation and dissipation of material or information over a period of time. Feedback loops are connected to these stocks and flows and serve as the building blocks for expressing the relationships between variables and overall dynamic behavior of complex interdependencies on the system. A key aspect of System Dynamics theory is the recognition of complex interdependencies among multiple feedback loops, and a rejection of simple linear cause-and-effect thinking, since in most systems the "effect" might also affect the "cause" (Sterman, 2000).

In System Dynamics models a "+" sign indicates a positive polarity between variables (i.e. as in Figure 2, as the number of Accidents increases, the level of Organizational Stress also increases). Similarly, a "-" link indicates a negative polarity between variables (i.e. as Safety Precautions increases, the number of Accidents decreases). The loop indicators such as "B1" indicate whether the loop is a balancing (B) or reinforcing (R) feedback loop as well as the loop identifier number (1, 2, 3…) which is used to distinguish between loops. Thus, loop "B1" should be read as "Balancing Loop 1." In reinforcing feedback loops, as seen in Figure 2, an increase in one variable (in this case Accidents) produces an increase in another variable (Organizational Stress), which then causes a greater increase in Accidents. In balancing feedback loops, however, an increase in one variable (in this case Accidents) produces an increase in another variable (Safety Precautions), which ultimately causes a decrease in the original variable. Finally, a causal arrow with two perpendicular straight lines,  represents a delay in the system.

Figure 2: The Effects of Reinforcing and Balancing Loops Over Time



Case Studies

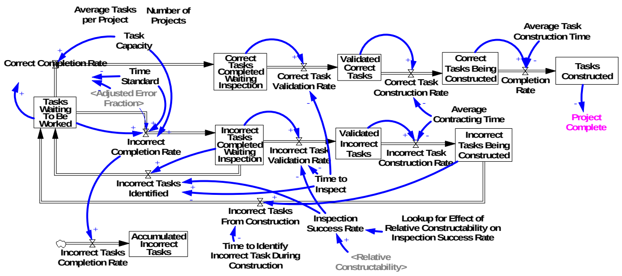
The remainder of this paper shows how researchers were able to use System Dynamics modeling to help reduce risk in two different organizations. The first case study addresses risk management in the project management realm, examining the Navy's construction design process (Minami et al, Improving the Naval Construction Process Through Lean Implementation, 2007). By modeling the construction design process and conducting multiple simulations, it became possible to make recommendations to policy makers that could help to decrease project completion time and save money. This is important because in the construction industry, delays and cost overruns are the rule rather than the exception in both the governmental and private construction industries (Ford and Sterman 2003, pp. 177-185).

The second case study addresses risk management from a safety standpoint. It shows how System Dynamics modeling was used to help explain how internal system feedback is involved in causing combat vehicle accidents in Iraq and Afghanistan (Minami et. al, Understanding Complexity: Dynamic Analysis of Combat Vehicle Accidents, 2007). This led to the identification of policy decisions that could best be implemented to help reduce combat vehicle accidents.

Case 1: Project Management

In order to help the Navy improve the construction design process, the following System Dynamics model was created and simulated. Figure 3 shows the Task Flow in Construction Design segment of the model, which represents the flow of tasks in construction design.

Figure 3: System Dynamics Model- Task Flow in Construction Design



The variable Tasks Waiting to be Worked represents the total number of tasks that must be completed by the General Contractor (GC) for a typical construction project. The Task Capacity and Adjusted Error Fraction regulates how fast the GC can complete the design of various tasks, and what ratio of them are completed correctly or incorrectly. Correctly completed tasks follow along the pipeline at the top; they are inspected for correctness, validated, and then are sent to the construction site to be built. Incorrectly designed tasks follow along the bottom pipeline; they are inspected for accuracy, which is governed by the Inspection Success Rate. If an Incorrectly Designed Task is caught in the Validation Phase, it then returns immediately to the Tasks Waiting to be Worked for rework. If not, the incorrect task is sent to the construction site to be built and the error is not found for several weeks. This is an important delay in the system, as not only is time wasted trying to build the incorrectly designed task, but there is an additional delay as arbitration and sometimes legal proceedings unwind between the GC and the Sub-Contractor.

The second segment of the System Dynamics Model titled Factors Contributing to Design Errors is shown in Figure 4. Conceptually, the error fraction for this study is determined by three components: Learning, Constructability and Design Sharing. The Adjusted Error Fraction in the model is determined by the product of the Effect of Constructability and Design Sharing on Error Fraction and Initial Error Fraction.

Figure 4: System Dynamics Model- Factors Contributing to Design Error

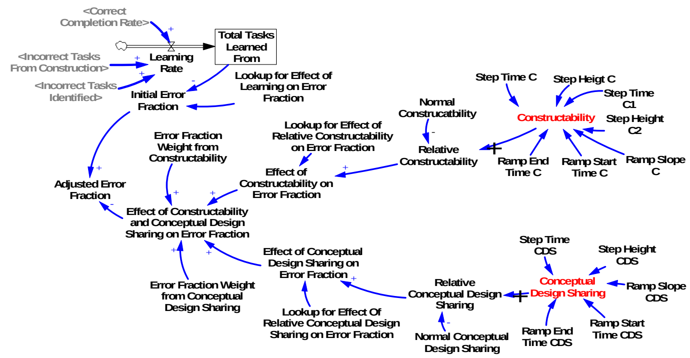
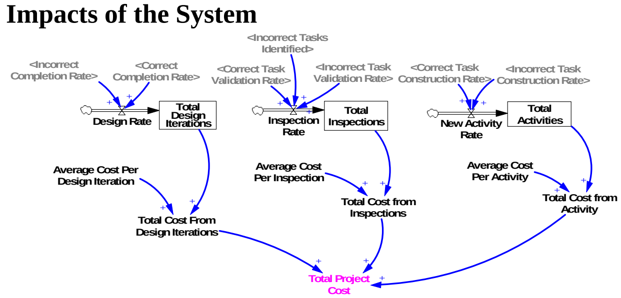


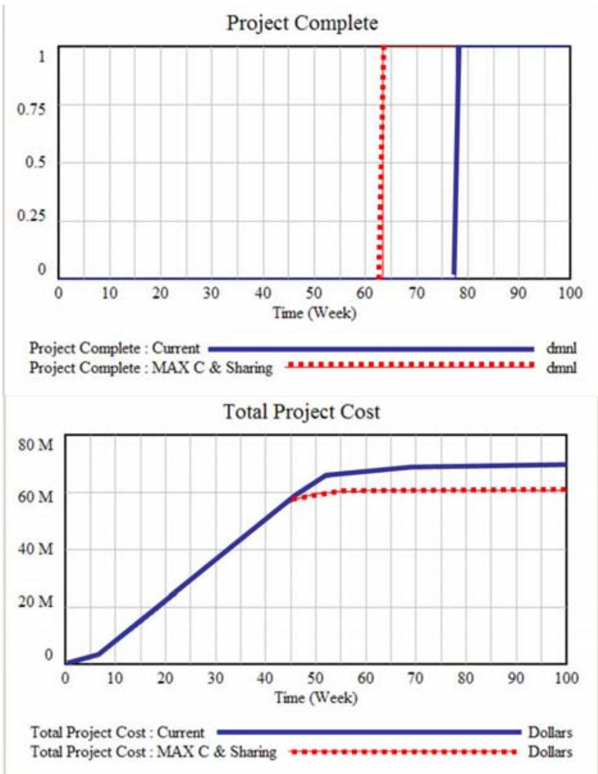
Figure 5 introduces the final segment of the model, "Financial Impacts of the System." This section of the model is very intuitive. It adds up the total number of design iterations (both correct and incorrect, where the number of incorrect tasks represents re-work), Total Inspections, and Total Construction Activities (abbreviated as Total Activities) as well as their associated costs and produces a final variable called Total Project Cost, which allows us to see the total cost of a given project for a specific simulation.

Figure 5: System Dynamics Model: Financial Impacts of the System



Many simulations were conducted, during which various exogenous variables were manipulated to determine which levers have the biggest impact on the system. The study found that by increasing constructability (the amount of interaction that takes place between designers, the general contractor, and sub contractors during the design phase of a project) as well as increasing design sharing among engineers within the design organization, resulted in a cost savings of nearly $10M or 14%, and a time savings of over 10 weeks (See Figure 6). Consequently, this study showed decision makers that improvements early in the design phase, specifically in regards to constructability and design sharing, would yield the biggest improvements in saving both time and money. This was an important finding because previously there had been a tremendous amount of focus on improvements downstream in the construction process, instead of upstream where the biggest problems were.

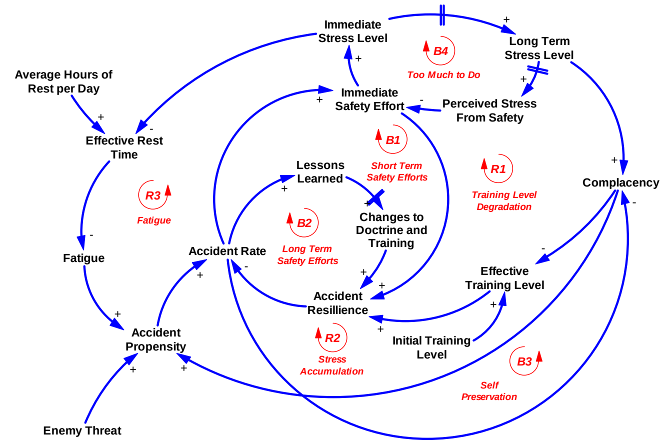
Figure 6: Output from Project Management Simulation



Case 2: Worker Safety

The second case study applies to employee risk management, and examined what the Army could do to reduce combat vehicle accidents. This is an important problem to the Army. Between the start of the war in Iraq in 2003 and April of 2007, approximately 20% of the Army's combat casualties were a result of accidents (over 600 total). During this time period, roughly 40% of the non-combat deaths in Iraq (about 250 total) were caused by combat vehicle accidents. These numbers are significant and represent the number of accidents from Iraq only; they do not include other accidents within the Army. Figure 7 depicts the high-level System Dynamics model that was created to examine this problem.

Figure 7 High-Level Model of Vehicle Safety

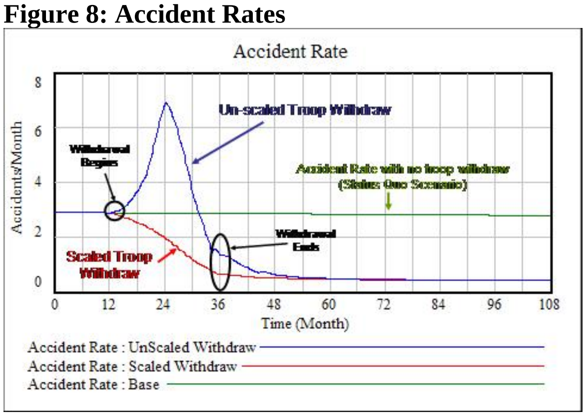


While it is outside the scope of this paper to describe all aspects of the model, a short explanation of one of the feedback loops involved in the model should help clarify the logic behind the modeling process. For example, Balancing Loop B1 (Short Term Safety Efforts) represents the dynamics of Short Term Safety Efforts on the system. As the Accident Rate increases, the Immediate Safety Effort undertaken by lower-level Army units increases, which leads to an increase in Accident Resilience and a corresponding decrease in the Accident Rate. Loop B1 is interesting because it describes the positive effects of knee-jerk reactions to a safety crisis (in this case an increase in the Accident Rate) (Carroll et al, 1998). In contrast, loops R1, R2 and R3 show the negative, or un-intentional side effects, of usually well intentioned knee jerk reactions.

After constructing this high-level conceptual model, data was collected from over 500 Army accident reports and dozens of interviews with Army officers to provide quantifiable measures for variables in the model, and to develop critical model parameters and equations. After collecting the data, a proof of concept model was created that transformed the high-level concept model of Figure 7 into a detailed model. The detailed model uses parameters for exogenous variables and equations for endogenous variables to create a mathematical model of the system that can be simulated by changing various exogenous variables over time. The model was then calibrated to ensure it could accurately depict historical accident rates for the Army, to ensure it was accurate and included all major feedback mechanisms. Figure 8 shows the calibration results of the model.

After demonstrating the validity and reliability of the model, dozens of simulations were conducted to see how the model could best be used to better inform policy decisions and help manage risk. While numerous insights emerged from these simulations, perhaps one of the most important was showing how the model could be used to better manage troop strengths and deployment/ re-deployment rates to help mitigate vehicle accidents. Figure 8 shows the output from the model using a troop withdrawal scenario. It demonstrates that proper scaling of troop withdrawals, or the careful management of with-drawling troops at a rate consistent with the drawl-down of the mission, is critical in preventing a spike in accidents during a redeployment operation.

Figure 8: Accident Rates



Ultimately, this study resulted in a number of potentially helpful recommendations for the Army. It showed that understanding delays in the system are critical in managing risk, while balancing how frequently troops conduct missions is also critical in this effort, as too few missions can result in complacency and too many missions can result in fatigue. It also demonstrated that managing troop exposure to the enemy, or how long soldiers remain in combat without a rest as well as how the Army conducts accident investigations plays a key role in managing operational safety risk.

Conclusion

There are many techniques and procedures already available to help organizations manage risk. Many of these existing techniques could be complimented by adding a systems approach to risk management that is likely to add value to most organizations. Further, System Dynamics is an excellent tool that provides both a methodology and software that can help model complex problems that are in need of risk management solutions.

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