D A Brief Introduction to System Dynamics Modeling

By focusing on the events immediately preceding accidents, event chains treat a system as a static, unchanging structure. But systems and organizations continually experience change and adapt to existing conditions. Systems dynamics models are one way to illustrate and model the dynamic change in systems. They have been primarily used to examine the potential undesired consequences of organizational decision making [194].

As noted in part I of this book, a system's defenses or safety controls may degrade over time because of changes in the behavior of the components of the safety control loop. The reasons for the migration of the system toward a state of higher risk will be system-specific and can be quite complex. In contrast to the usually simple and direct relationships represented in event-chain accident models, most accidents in complex sociotechnical systems involve relationships between events and human actions that are highly nonlinear, involving multiple feedback loops. The prevention of accidents in these systems therefore requires an understanding not only of the static structure of the system (the *structural complexity*) and of the changes to this structure over time (the *structural dynamics*), but also the dynamics behind these changes (the *behavioral dynamics*). System dynamics provides a way to model and understand the dynamic processes behind the changes to the static safety control structure: how and why the safety control structure might change over time, potentially leading to ineffective controls and unsafe or hazardous states.

The field of system dynamics, created at MIT in the 1950s by Jay Forrester, is designed to help decision makers learn about the structure and dynamics of complex systems, to design high leverage policies for sustained improvement, and to catalyze successful implementation and change. System dynamics provides a framework for dealing with dynamic complexity, where cause and effect are not obviously related. It is grounded in the theory of nonlinear dynamics and feedback control, but it also draws on cognitive and social psychology, organization theory, economics, and other social sciences [194]. System dynamics models are formal and can be executed. The

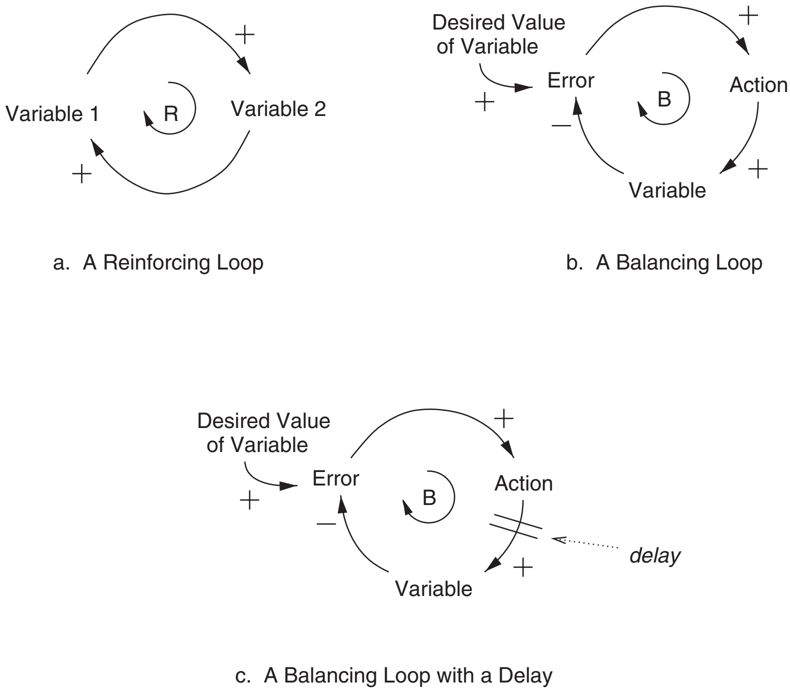

Figure D.1
The three basic components of system dynamics models.

models and simulators help to capture complex dynamics and to create an environment for organizational learning and policy design.

System dynamics is particularly relevant in safety engineering when analyzing the organizational aspects of accidents and using STPA on the higher levels of the safety control structure. The world is dynamic, evolving, and interconnected, but we tend to make decisions using mental models that are static, narrow, and reductionist. Thus decisions that might appear to have no effect on safety—or even appear to be beneficial—may in fact degrade safety and increase risk. System dynamics modeling assists in understanding and predicting instances of policy resistance or the tendency for well-intentioned interventions to be defeated by the response of the system to the intervention itself.

System behavior in system dynamics is modeled by using feedback (causal) loops, stock and flows (levels and rates), and the nonlinearities created by interactions between system components. In this view of the world, behavior over time (the dynamics of the system) can be explained by the interaction of positive and negative feedback loops [185]. The models are constructed from three basic building blocks:

positive feedback or reinforcing loops, negative feedback or balancing loops, and delays. Positive loops (called reinforcing loops) are self-reinforcing, while negative loops tend to counteract change. Delays introduce potential instability into the system.

Figure D.1a shows a *reinforcing loop*, which is a structure that feeds on itself to produce growth or decline. Reinforcing loops correspond to positive feedback loops in control theory. An increase in variable 1 leads to an increase in variable 2 (as indicated by the "+" sign), which leads to an increase in variable 1, and so on. The "+" does not mean that the values necessarily increase, only that variable 1 and variable 2 will change in the same direction. If variable 1 decreases, then variable 2 will decrease. A "–" indicates that the values change in opposite directions. In the absence of external influences, both variable 1 and variable 2 will clearly grow or decline exponentially.

Reinforcing loops generate growth, amplify deviations, and reinforce change [194].

A *balancing loop* (figure D.1b) is a structure that changes the current value of a system variable or a desired or reference variable through some action. It corresponds to a negative feedback loop in control theory. The difference between the current value and the desired value is perceived as an error. An action proportional to the error is taken to decrease the error so that, over time, the current value approaches the desired value.

The third basic element is a *delay*, which is used to model the time that elapses between cause and effect. A delay is indicated by a double line as shown in figure D.1c. Delays make it difficult to link cause and effect (dynamic complexity) and may result in unstable system behavior. For example, in steering a ship there is a delay between a change in the rudder position and a corresponding course change, often leading to overcorrection and instability.