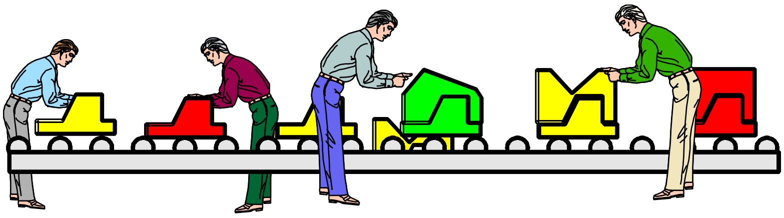
Strategos, Inc.
3916 Wyandotte
Kansas City MO 64111 USA
816-931-1414

A Systems View of Scheduling



By
Quarterman Lee, P.E.
Strategos, Inc.

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A Systems View of Scheduling

This paper draws from several branches of Engineering and Physics while avoiding advanced mathematics. We begin with a review of feedback systems (most scheduling systems fall in this category). We then discuss instability in such systems. Instability and fast response are often opposed in such systems and this often creates significant problems for the designers and users. The new branch of Physics known as Chaos Theory can also contribute to our understanding because chaos is actually quite common in scheduling and other business systems.

Jay Forrester was an expert on feedback systems and designed fire control systems during World War II, In the early 1960's he investigated the application of system theory to a wide range of business and industrial systems. His book, "Industrial Dynamics," has become a classic. Peter Senge and others at the Massechussetts Institute of Technology extended this work in more recent times.

While this chapter is primarily conceptual and theoretical, a basic understanding will be invaluable later. Such understanding can help designers avoid errors in the initial setup of a Kanban system. It can also help to understand actual performance, improve that performance and trouble-shoot problems.

Feedback System Basics

Kanban, and most scheduling and inventory control systems, are "feedback systems", i.e. they sense the current state of the system, compare it to a desired state and initiate action to correct any discrepancy. Feedback systems are also known as "cybernetic systems."

Feedback System Example

Feedback systems are common in everyday life as illustrated by the home heating system of figure 3-1. In this system, the controlled variable is "Room Temperature." The system is designed to maintain this room temperature very close to the desired temperature as indicated by the "Set Point" on the room thermostat.

When the furnace receives a signal for heat from the thermostat the burner ignites. After a minute or so, when the heat exchanger has come to temperature, the circulation fan starts and circulates hot air into the room space. As the hot air mixes with room air, the room temperature rises. When the thermostat senses that the room air temperature has reached the set-point, it signals the furnace to turn off. The gas valve closes and the burners shut down. However, the heat exchanger remains hot. The circulation fan continues for several minutes until the heat exchanger cools and then the circulation fan shuts down.

The "*forward loop*" consists of the furnace and the room air. The thermostat and signal wires constitute the "*feedback loop*." In this case it is the primary feedback loop.

The narrow blue line of figure 3-2 shows the resulting room temperature over time. Notice that it varies between 74 and 76 degrees. One reason for this variance is the "deadband" of the thermostat. A second reason is the time delay between the thermostat's signal to start or stop and the actual change in output of hot air.

*Deadband***—**the thermostat is designed to start or stop the furnace only when the difference between set-point and room temperature is greater than about 1.0 degree. This is necessary because without a deadband, the furnace would start and stop every few seconds with the most minute change in room temperature. The effect is to allow a small variance in room temperature over time.

Time Delay—once the thermostat signals for startup or shutdown, there is a time delay while the heat exchanger gets hot or cools down. This time delay causes a further variation in room temperature. While the heat exchanger is warming, the room temperature continues to fall. Likewise, when the heat exchanger is cooling at the end of a cycle it continues to add heat to the room even after the thermostat has called for shutdown.

This illustrates two reasons why feedback systems become unstable: time delays and non-linearity. Non-linearity refers to a response that is not proportional to input. The dead-band is non linear. A small temperature change brings no response from the thermostat. A slightly larger change starts the burner at full heat. The burner is either on or off and is also non-linear. A burner that could modulate and produce heat in proportion to the temperature difference between setpoint and room temperature would be more linear and, thus, more stable.

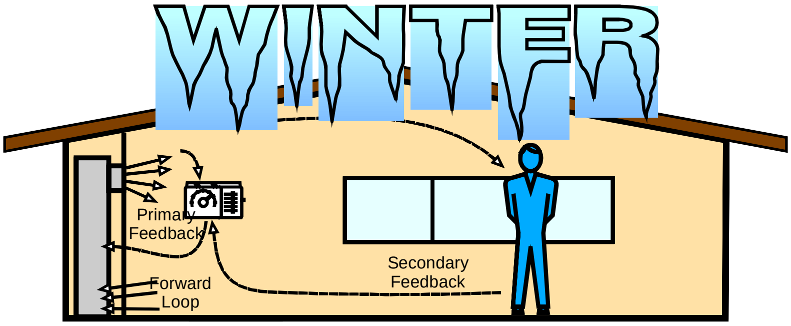


Figure 0-1 Home Heating--A Common Feedback System

In this heating system, operating on its own, the time delays and non-linearity produce only small oscillations and system instability is so small that it is acceptable. In some situations, however, such a system can become very unstable.

There are times when an additional feedback loop is introduced into a formerly stable heating system. This takes the form of a thermostat fiddler. Thermostat fiddlers are people who attempt to improve on the control system by changing the set-point frequently. Perhaps they are hypersensitive to temperature or there may be a genetic defect. Whatever the cause, they sense the slight decrease in temperature and respond by adjusting the thermostat set-point.

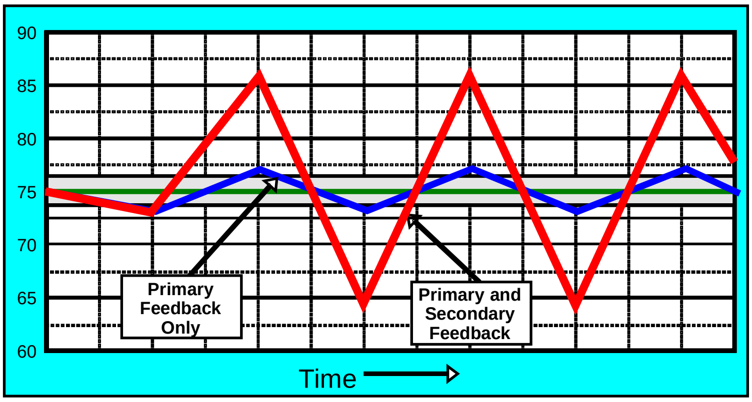


Figure 0-2 Temperature Variation In The Heating System

The broad line in figure 3-2 illustrates the results. When the fiddler detects a slight decrease in temperature, he/she raises the set-point to a very high setting, say 85 degrees. The thermostat responds, the burner ignites and, after a few minutes, room temperature starts to rise. The fiddler rarely notices the rising temperature until it reaches a high value, say 80 degrees or so. He/she responds by excessively lowering the of set-point and simultaneously cursing what they perceive as a defective furnace.

This illustrates the effect of amplification in the feedback loop. The temperature difference signal is amplified out of proportion and over-correction results. This is a common phenomenon when humans become part of a control system. With scheduling and inventory systems, it results in excessively large batches of product and excessively large inventory usually alternating with shortages.

Another Feedback System Example

The guidance system of the Sidewinder air-to-air missile was remarkably simple and effective. The variable to be controlled was the angle, a, between the heading of the missile and the line-of-sight or bearing to target. If this angle is maintained at zero degrees, the propulsion system will close the distance and the missile will hit the target.

Figure 3-4 is a simplified illustration of the guidance system. In this system infra-red radiation from the target’s engine exhaust reflects from a parabolic mirror in the nose of the weapon When the angle (alpha) is zero, this radiation enters along the axis of the missile and reflects along the same axis. If the radiation enters from a non-zero angle (as shown) the reflection strikes an array of photo-sensors. A guidance computer interprets electrical signals from the photo-sensors and drives steering fin actuators to change the heading of the missile.

- Forward Loop—Actuator, fins and aerodynamic characteristics
- Feedback Loop—Optical sensor and guidance computer

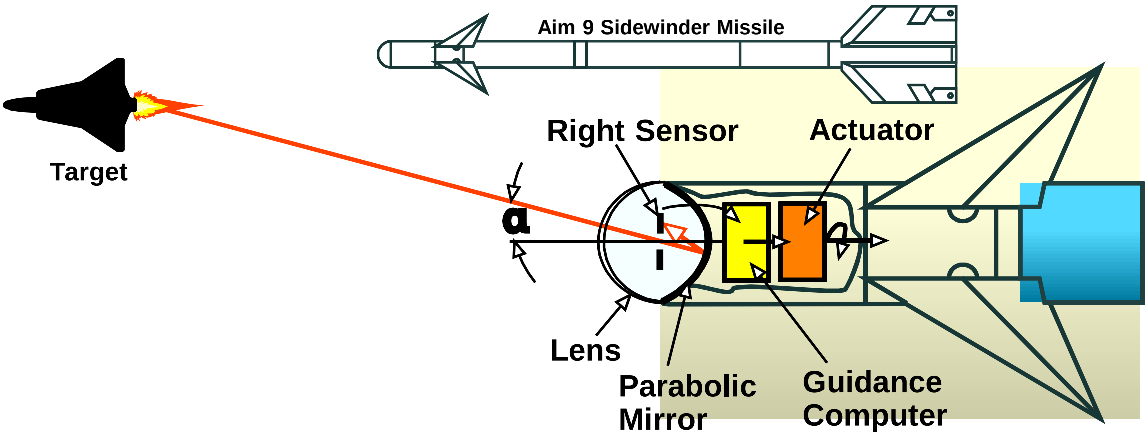


Figure 0-1 Feedback In the Sidewinder Guided Missile

The computer intentionally amplifies the signal to “over-control” the system because the target may be maneuvering. As a result, the missile typically follows a zig-zag path as in figure 3-5. It overshoots the desired set-point and then reverse compensates to home on the target. This amplification is a sensitive parameter. Amplification allows the missile to follow a rapidly maneuvering target more accurately and to “anticipate” its future heading. With more amplification, the zig-zags would grow instead of diminish, sending the missile wide of its target. A delay between the time the sensor detects the target bearing and the actual change in heading of the missile also contributes to this overshoot.

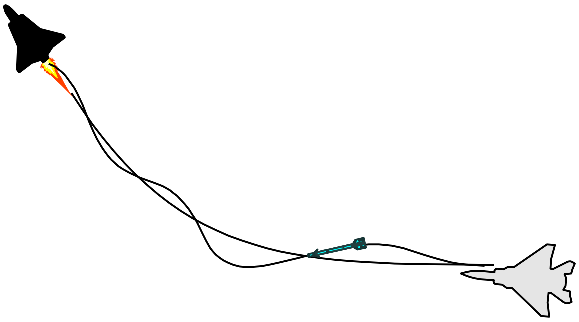


Figure 0-2 Over-control In The Sidewinder

Instability In Feedback Systems

In some feedback systems amplification continues with each cycle resulting in larger and larger excursions from the set-point. Figure 3-3 illustrates. In theory, the controlled variable in such a system eventually oscillates to infinity. In reality, some physical constraint limits the excursions. For example, inventory and shortages may alternate getting larger and larger until the warehouse is full and there is no room for additional inventory. The company may run out of cash to pay for the inventory and thus force limitation. There is lots of inventory but never the right inventory.

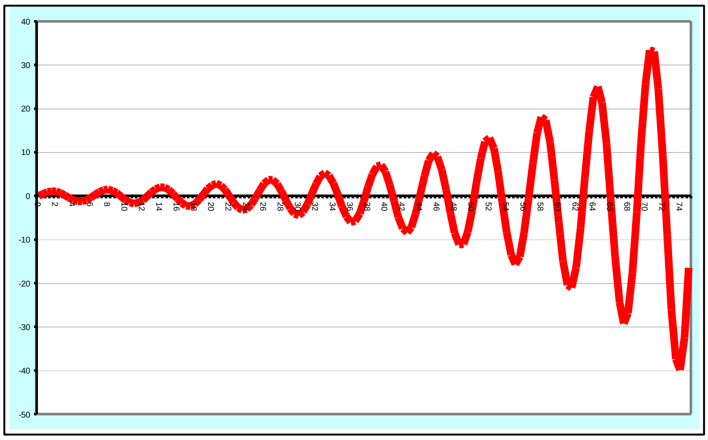


Figure 0-1 Instability In A Feedback System

Instability results primarily from amplification and time delays. Time delays in the feedback loop have larger effects than in the forward loop but any unnecessary amplification can contribute to instability.

These affects are common in everyday life. Most of us have heard the awful squeal that sometimes affects public address systems. In such a situation, the speakers voice enters a microphone. An amplifier increases the signal and sends it out via loudspeakers. When the signal from the loudspeakers reenters the microphone it is amplified a second time, a third time and so on. The signal increases until the limits of the amplifier or speaker have been exceeded.

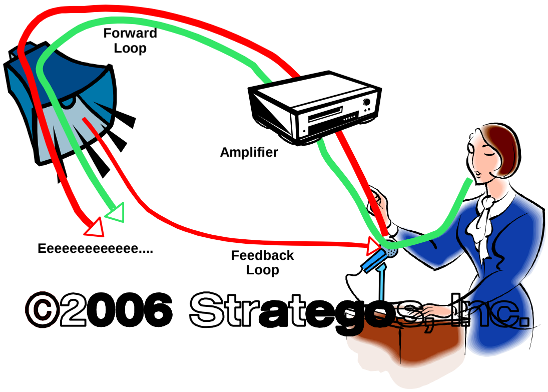


Figure 0-2 Instability In A Public Address System

Complexity and Ashby's Law

W. Ross Ashby developed much of the theory of cybernetic systems in the 1950's. Ashby's Law concerns the relationship of a control system to the system it attempts to control. One version of Ashby's Law is in the box at right.

Ashby's Law

"The complexity of a control system must be equal to or greater than the complexity of

Ashby's Law tells us that a complex system requires a complex controlling device. Conversely, simple systems require only simple controllers for successful operation.

The implication for Kanban and for Lean Manufacturing is that we should first simplify the process. Kanban is a simple system best suited for controlling simple processes. That does not mean that the process technology of each operation must be simple; only that the number of steps, the material paths and the number of variations that affect the inventory should be simple.

For example, the actual casting of steel is, from the physical standpoint, very complicated. It involves complex heat transfer, fluid mechanics and metallurgy. The molding and core sand must be strong under intense heat but thereafter disintegrate for easy shakeout. The steps in casting steel, however, can be quite simple:

1. Make The Cores
2. Make The Cope And Drag
3. Assemble Cores, Cope & Drag
4. Pour The Metal
5. Cool And Solidify
6. Shake Out The Sand
7. Remove Fins And Risers

This example could be even simpler by combining steps 1,2 and 3 in a "Mold-Making Workcell." Kanban could be very effective in controlling the inventory, timing and production of this process.

Chapter 4 expands on this issue.

How Cellular Manufacturing Reduces Complexity

A workcell is a work unit larger than an individual machine or workstation but smaller than the usual department. Typically, it has 3-12 people and 5-15 workstations in a compact arrangement. An ideal cell manufactures a narrow range of highly similar products. Such an ideal cell is self-contained with all necessary equipment and resources. Figure 3-7 is a typical assembly workcell with four people. They assemble and test a line of small diaphragm pumps.

Cellular layouts organize work around a product or a narrow range of similar products. Materials sit in an initial queue when they enter the cell. Once processing begins, they move directly from process to process (or sit in mini-queues). The result is very fast throughput.

Simplicity is an underlying theme throughout cellular design. Notice the simplicity of material flow. Scheduling, supervision and many other elements also reflect this underlying simplicity.

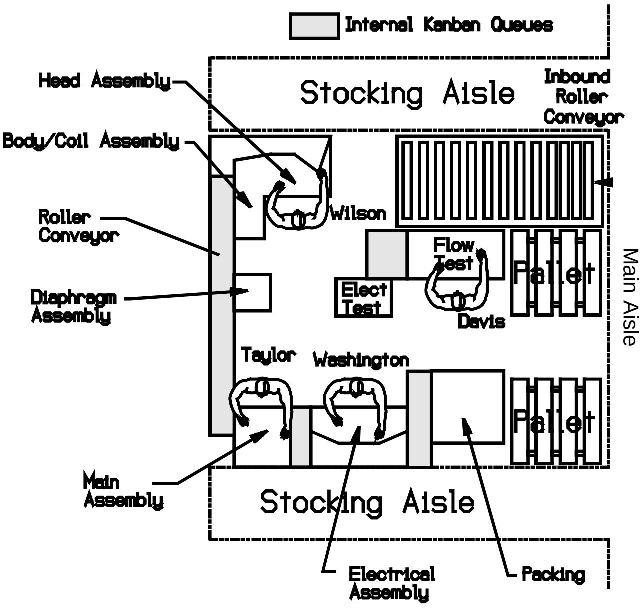


Figure 0-1 Assembly Cell for Small Pumps

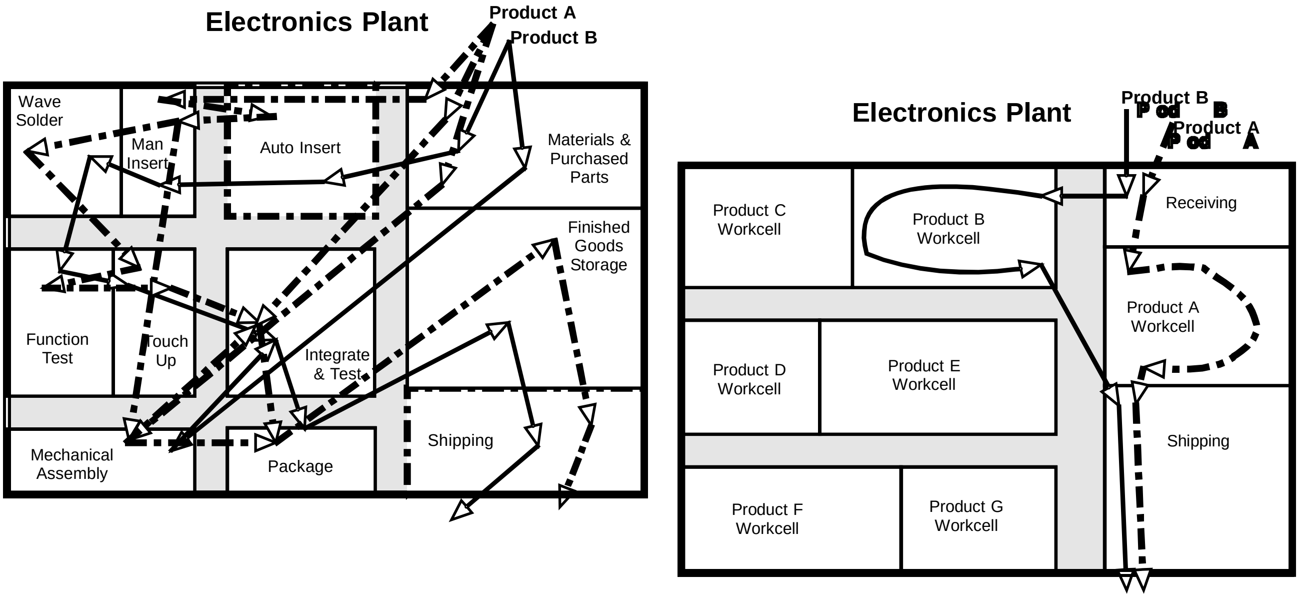


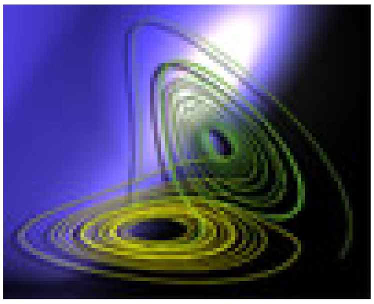
Figure 0-2 Functional & Cellular Layouts

Figure 3-8 contrasts functional layouts, and cellular operations. The example is from an electronics plant. In the functional configuration, departmental organization is by function (or process). Since each printed circuit board requires all (or most) processes, it travels to every department. In each department, it sits in queue waiting for processing. Ten process steps require ten queues and ten waits. Travel distances are long, communications difficult and coordination is messy. Our article on Lean Manufacturing Benefits has considerably more detail or you can download the Workcell Design chapter from Mr. Lee's latest book.

Cellular Manufacturing seems simple. But beneath this deceptive simplicity are sophisticated Socio-Technical Systems. Proper functioning depends on subtle interactions of people and equipment. Each element must fit with the others in a smoothly functioning, self-regulating and self-improving operation. This simplicity is only achieved through a rigorous design process.

Either of the layouts in figure 3-8 might employ Kanban as the scheduling method. However, it would be much simpler and easier to use Kanban in the cellular layout because each product would only require only 2-4 Kanban links. The functional layout would require dozens of Kanban links making the overall Kanban system more difficult and complex. This is Ashby's Law in action.

Chaos

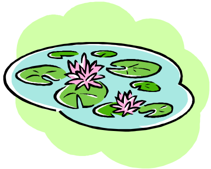


Chaos is a branch of physics that studies the behavior of unpredictable systems. Chaos theory is one of the major scientific developments of the twentieth century. *Chaotic systems are governed by precise deterministic evolution equations, but have unpredictable and seemingly random behavior*.

The atmosphere is a chaotic system, and as a result, small errors in our estimate of the current state can grow to have a major impact on the subsequent forecast. Stated in another way, a butterfly flaps its wings in Hawaii and affects the weather in Chicago two weeks later. . In practice, this limits detailed weather prediction to about a week or so ahead.

Many such systems exist in our everyday environment. They include weather systems, dripping faucets, and beating hearts. Inventory systems often are chaotic. All chaotic systems are feedback systems in the sense that their future state depends on the current state of the system.

Chaotic system Example



Biologists have long noted that certain micro-ecological systems, such as a farm pond, experience wide and unpredictable fluctuations in the seasonal population of particular species such as fish. It was assumed that these fluctuations resulted from external influences such as weather or disease.

In the early 1970's, Robert May, a biologist from Australia, investigated a very simple model for the population of fish in a pond. Prior to May's work, *it was assumed that simple equations, representing simple systems, produce simple system behaviors.* May's work demonstrates that this is not always so. Under certain conditions, even simple equations can produce complex and unpredictable behavior.

May's equation is below (Eq 3-1). N equals the number of fish in the pond in thousands. The term "K" is a growth factor that depends upon the fecundity of the particular species. To find the population for a given season (i), take the previous season's (i-1) population multiplied by "k" and multiplied again by one minus the previous season's population. By starting with a particular known population, the population in each succeeding season is calculated. Simple enough.

N=Number of Fish In Pond (In Thousands)
K=Growth Factor

$$N_i = k*N_{(i-1)}*(1-N_{(i-1)})$$

Equation 0-1 Annual Fish Population

Figure 3-9 shows the fishpond population when the growth factor (k) is small. Starting with one fish, the population rises for several seasons until the food supply limits further growth.

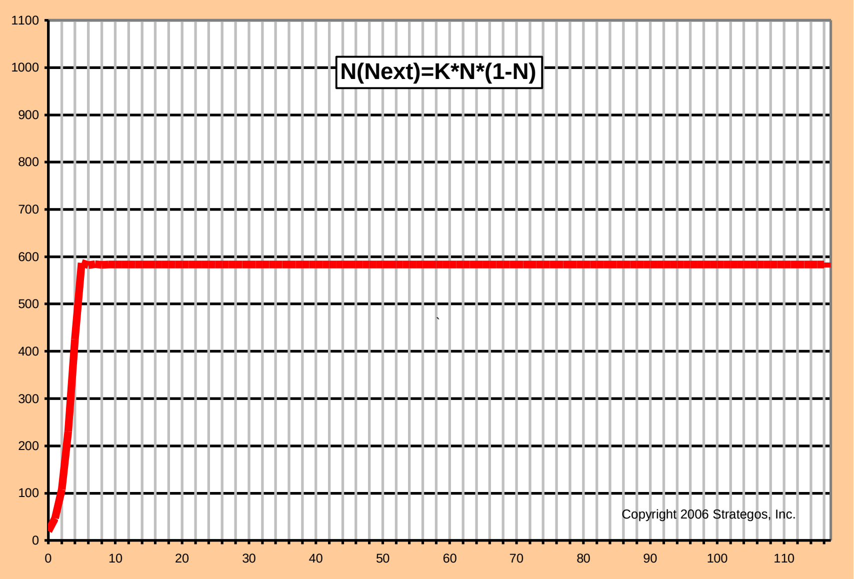


Figure 0-1 Fishpond With Small Growth Factor

With a somewhat higher growth factor, as in figure 3-10, the population overshoots. Too many fish hatch for the food supply and many die. The system oscillates between a higher and lower population but eventually stabilizes.

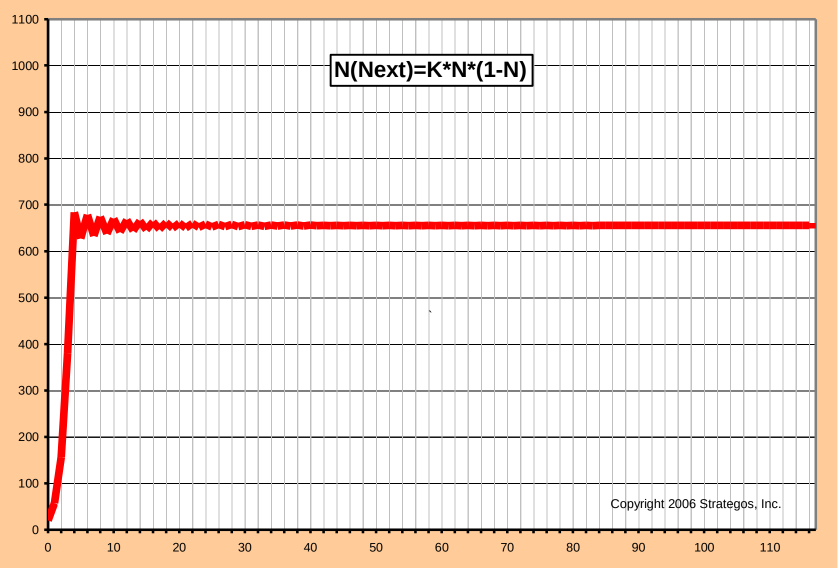


Figure 0-2 Higher Growth Factor Brings Oscillation

A bit higher growth factor as in figure 3-11 and the oscillation persists much longer. Higher yet as in figure 3-12 and the oscillation never decays.

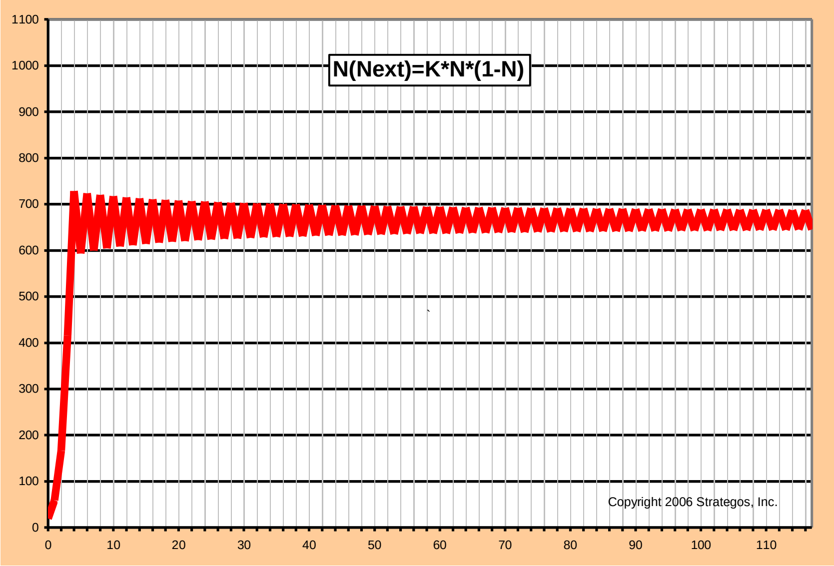


Figure 0-3 An Even Higher Growth Factor Brings Slower Decay

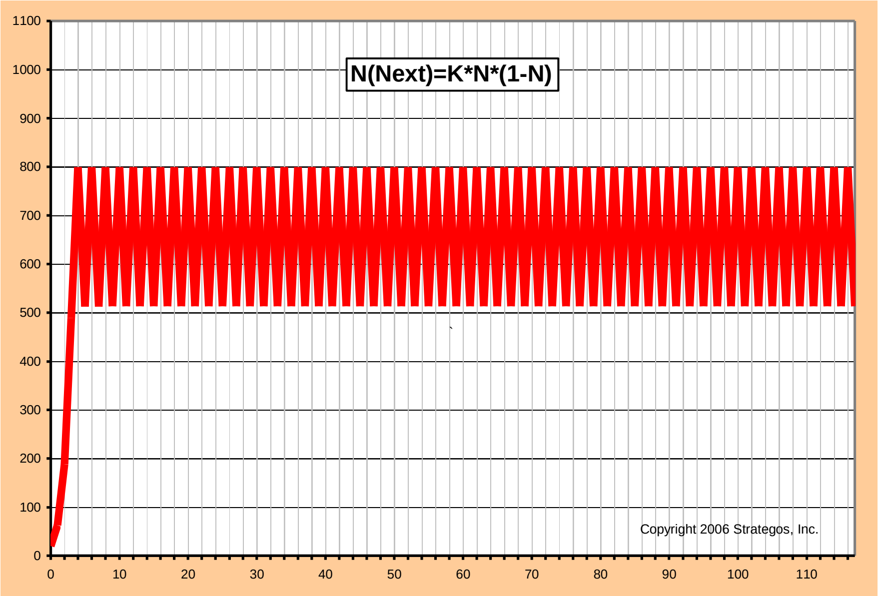


Figure 0-4 Steady State Oscillation

In the next stage, figure 3-13, the oscillation becomes more complex and the period of oscillation doubles and then doubles again. Nevertheless, the system is predictable and there is a definite pattern.

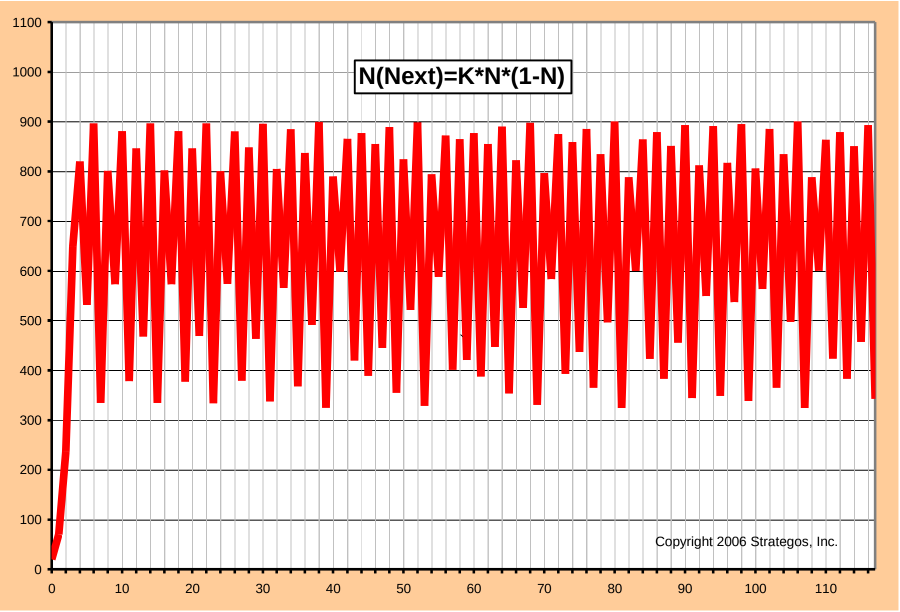


Figure 0-5 Period Doubling and Complex Oscillation

Finally, the system becomes chaotic. While there appear to be somewhat repetitive patterns, they occur at different intervals. The future state at any particular time period is not predictable from past behavior. Moreover, any small change in the initial population would give significantly different results in any particular future season.

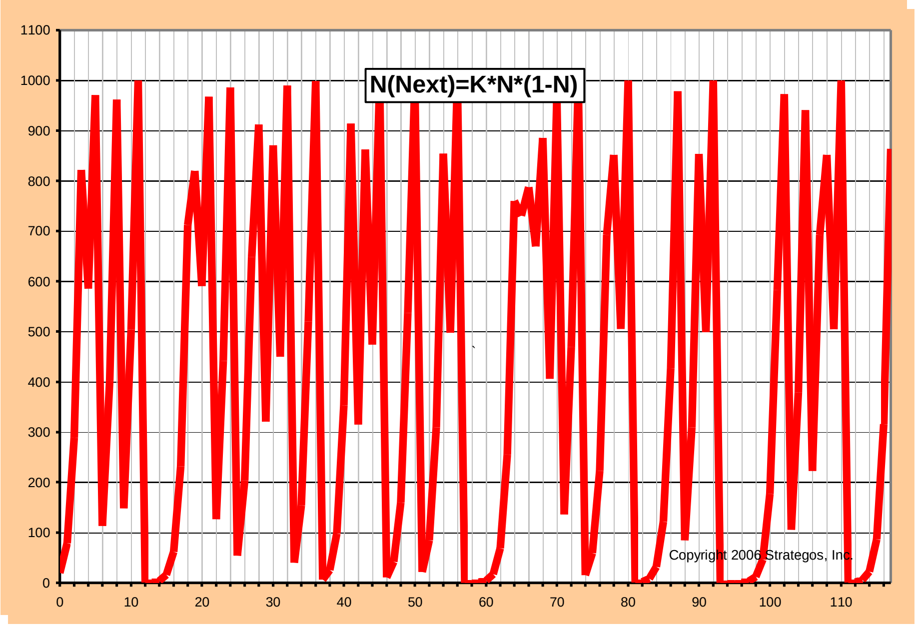


Figure 0-6 Fishpond Driven To Chaos

Note, again, that this behavior is generated entirely by the system through deterministic equations. No external randomness has been introduced in the form of weather or other environmental change. If external randomness were superimposed on such a chaotic system, it would be impossible to discriminate between the effects of internal randomness and the external changes. Most people, including scientists for many years, attributed chaotic effects entirely to external randomness because the idea of a deterministic system that generates in own random behavior is so counterintuitive. Yet, we find many, many chaotic systems in nature and in man-made systems.

Chaotic Behavior In A Simple Inventory System

The charts of figures 3-15 and 3-16 show the on-hand balance for six part numbers in an actual factory. Note the seemingly random pattern. The inventory system was a simple Re-Order Point system with steady demand. There should be some semblance of the classic saw-tooth pattern. Moreover, the demand for each of these products was roughly proportional over time—for every ten 4M24's sold there should have been two 4M90's sold. This proportional demand is also not reflected in the inventory.

While there were many external random factors in this situation there is also good reason to believe that the system itself was unstable and/or chaotic. Given the complexity, time delays and feedback amplification in most production systems, instability and chaos is probably endemic. It is just hidden by ignorance of these systems and general blaming on specific external factors.

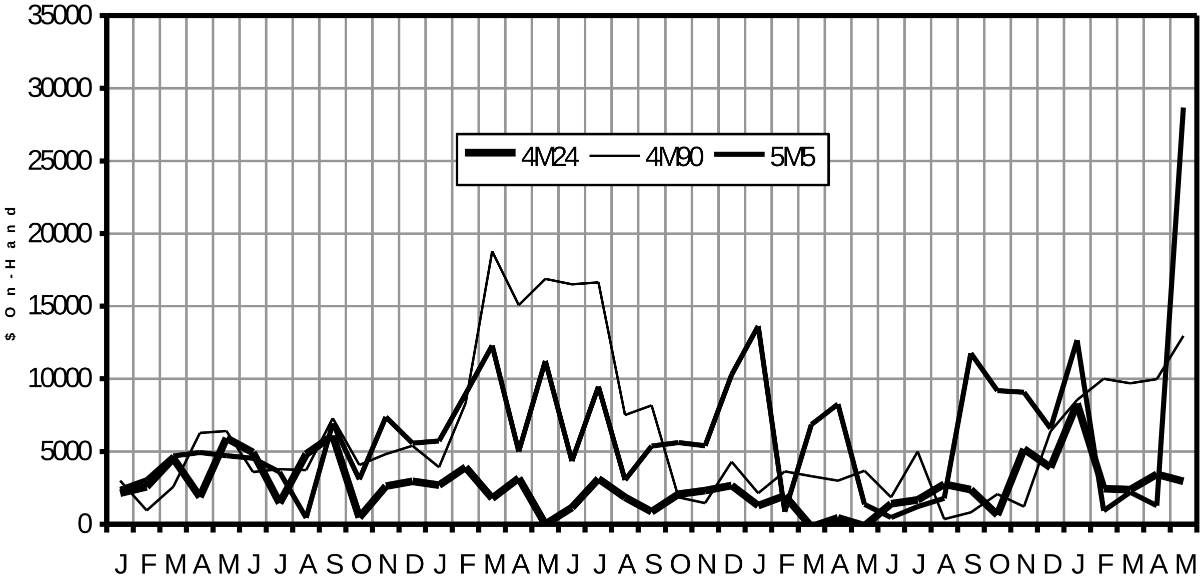


Figure 0-7 On-Hand Inventory For Three Products

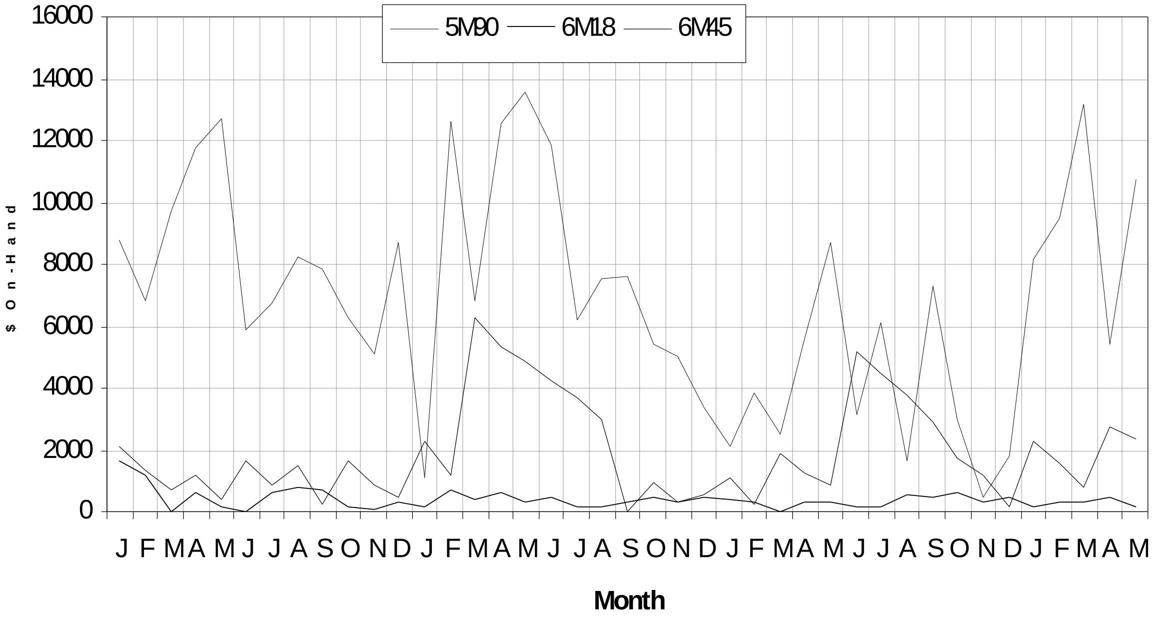


Figure 0-8 On-Hand Inventory For Three Additional Products

Applying The Knowledge

An important question is “What to do, if anything, with our limited knowledge of instability and chaos?” A detailed study to determine whether chaos is present in a scheduling system is limited by the complexity of such systems and the need for sophisticated and time-intensive mathematics. Moreover, sorting out true chaos from external randomness is near-impossible.

What we can do is understand the fundamental causes and effects and then minimize these causes within inventory systems. This is what Toyota did in their early lean efforts even though their knowledge was vague and intuitive.

Root Causes of Instability and Chaos

Preventing or reducing instability and chaotic behavior is one of the most important goals for stabilizing scheduling and inventory systems. We have shown examples of some of the fundamental causes of this behavior. There are several basic causes of instability and chaos some of which we illustrated in earlier examples:

- Time Delays
- Amplification
- Complexity
- Non-Linearity

Time Delays—the most ubiquitous cause of instability in inventory systems. They are especially destructive in the feedback or information loops. Batching is the most common form of time delay. In the forward loop we often batch products which sit for hours, days, weeks or months. In the information loop we often batch transactions prior to entry in an MRP/ERP system. Kanban is a form of batching but the batches tend to be very small and the time delays short.

In MRP/ERP systems, time delays are especially common. For example, the system assumes a fixed delivery time for suppliers or workcenters. In fact, such times are highly variable. There is a very strong tendency to inflate these delivery times to cover the worst-case scenario. As a result, the system assumes much longer lead times than actually would occur in most instances.

Amplification—occurs primarily from the human elements. Buyers order more than is necessary, "just in case…" Production supervisors overbuild because the machine is already setup. There are many such examples.

Complexity—Complex systems are more prone to chaos than simple systems although, under the right conditions, even simple systems can be chaotic. The fish pond, for example, is a simple system that is chaotic for certain growth factors.

Non-Linearity—Linear systems have a response that is proportional to the input. The classic tale of "The Straw that Broke The Camel's Back" is an example of non-linearity. In this tale, a camel driver loads a camel with goods and its back sags. He loads more and it sags a bit more. Finally, the driver places a small straw on the load and this straw, combined with the previous load, breaks the camel's back. Re-order point systems are similar. Withdrawals occurs in a reorder point system and nothing happens. Then, when the reorder point is reached, the system triggers a very large order for re-supply, even though the final withdrawal may have been very small.

Minimizing Chaos and Instability

To effectively minimize chaos and instability it is necessary to deal with the root causes. Table 3-1 summarizes these root causes and some common preventive strategies. Note that Kanban, by its nature, addresses most of the root causes. However, Kanban is most effective when implemented along with the other prevention tactics such as cellular manufacturing and setup reduction.

Cause	Prevention Tactics
Reduce Time Delays	• Enter Transactions Immediately • Reduce Batches & Queues
Minimize Amplification	• No Arbitrary Increases On Orders • Eliminate Overproduction • Order/Build Frequently In Small BatchesRestructure Feedback Loops • Disseminate Information Widely • Correct Variations Immediately
Complexity	• Cellular Manufacturing • Simplify The Process • Flatten BOMS • Employ TQM • Simplify Product Mix
Minimize Non-Linearity	• Implement Kanban • Close Min-Max Points

Table 0-1 Minimizing Instability & Chaos

What To Remember

- Most scheduling systems are feedback systems in which the future state of the system depends upon the current state.
- Feedback systems are subject to instability and chaos.
- Chaotic systems are feedback systems governed by precise deterministic evolution equations, but have unpredictable and seemingly random behavior.
- Ashby’s Law implies that complex scheduling systems are required to regulate complex processes. When processes are simplified (as in Cellular Manufacturing) the scheduling system can be simplified.
- Since complexity is a root cause of chaos and instability, simple processes and simple control systems are highly beneficial.
- To Minimize instability and chaos:
    - Keep It Simple
    - Implement Flow Lines & Cells
    - Employ Kanban, Direct Link & Broadcast wherever Possible
    - Reduce All Time Delays
    - Schedule Frequently
    - Increase Linearity
    - Minimize Unnecessary amplification