A System Dynamics Model of How Managers Learn to Allocate Resources During Process Improvement

by

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at the

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ABSTRACT

Many firms have successfully implemented process improvement techniques, increasing both quality and productivity. Yet, for every successful process improvement implementation, there are many more failures. Intrinsic lack of efficacy is not the cause of these failures. Evidence suggests that, if the process improvement techniques were implemented effectively, the initiatives would have succeeded, and the organizations would have benefited. Two groups of scholars have developed widely different bases—one physical and one behavioral—for their theories of how to implement change successfully within an organization. Unfortunately, neither the physical nor the behavioral body of theory can explain why organizations fail to implement useful process improvement initiatives successfully. This thesis ties together elements of the physical and behavioral theories to create an integrated, interdisciplinary system dynamics model. New process capability, perception, and learning structures are developed in this model. The physical process structures and scarce resources give rise to Optimal Throughput and Optimal Yield. We then show how our manager perceives and learns over time the instrumental effectiveness of the process improvement technique and decides how to allocate scarce resources toward or away from the process improvement initiative. We demonstrate the “worse before better” dynamics mentioned in the literature. The analysis of the model suggests three new states of perception and learning that characterize a process improvement implementation. We then compare a manager with “perfect process information” with a more reasonable, boundedly rational one. Finally, we show how systems with lower initial capability produce more clear-cut information about the instrumental effectiveness of the process improvement techniques and, therefore, have more successful implementations.

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Foreward

The following thesis emerges from two papers: “A Simulation-Based Approach to Understanding the Dynamics of Innovation Implementation” (Repenning forthcoming) and “Getting Quality the Old-fashioned Way: Self-confirming Attributions in the Dynamics of Process Improvement” (Repenning and Sterman 2000). The first paper develops the idea of the dynamics of process improvement implementation and lends the ideas of normative and instrumental motivation in the dynamics of process improvement implementation to this thesis. The second paper discusses role of misattributions in the failure of process improvement initiatives and provides the concepts of Working Harder and Working Smarter as ways to meet throughput demands to this thesis. Three key insights in this thesis result from the combination of these two papers. First, we have articulated the Working Harder and Working Smarter loops as elements of the instrumental motivation. Second, although we have omitted the important dynamics of diffusion in the adoption of process improvement, we have added the roles of process throughput and the resources constraint to “A Simulation-Based Approach to Understanding the Dynamics of Innovation Implementation.” Third, we have translated the causal loop diagrams in “Getting Quality the Old-fashioned Way: Self-confirming Attributions in the Dynamics of Process Improvement” into a formal simulation model. As Nelson Repenning and John Foster will hopefully publish this thesis as a paper, we have “platform reused” much of the text from these two papers in this thesis.
Acknowledgements

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- The Coffeehouse, Dome Café, and, especially, caffeinated beverages
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1. Introduction

1.1 Background and Motivation
Many firms have successfully implemented process improvement techniques, increasing both quality and productivity. Easton and Jarrell (1998) found that firms that commit long-term to process improvement outperform their competitors in profitability and stock returns. Hendricks and Singhal (1996) also found that firms that win quality awards – an assumed indicator of successful process improvement initiatives – surpass their counterparts in terms of share price.

Yet, for every successful process improvement implementation, there are many more failures (Ernst & Young 1991, GAO report 1990, Hammer and Champy 1993, White 1996). The GAO (1990) found that early Baldrige award finalists did no better than comparable nonfinalists in sales growth or profitability.

Even more disturbing, some initially successful process improvement programs fail in the long run. Kaplan (1990 a, b) and Sterman, Repenning, and Kofman (1997) describe the case of Analog Devices, a major semiconductor manufacturer, who improved quality and productivity substantially but later suffered declining profits, a sharp drop in share price, and a major layoff.

Even when process improvement techniques are implemented successfully, Hendricks and Singhal (1996) found that large firms experience abnormally low returns in the two years prior to winning a quality award, giving evidence to a “worse before better” dynamic in process improvement.
Why do some process improvement implementations succeed while others fail? Why do some succeed initially yet fail over time? And, why are award-winning implementations preceded by abnormally low returns? Intrinsic lack of efficacy is not the cause of failure. Compelling evidence suggests that, if the process improvement technique were implemented effectively, the initiative would have succeeded, and the organization would have benefited. For example, while numerous studies conclude that the dedicated use of TQM improves quality, productivity, and overall competitiveness (Easton and Jarrell 1998, Hendricks and Singhal 1996, Barron and Paulson Gjerde 1996), a recent survey found that among U.S. managers TQM is "...deader than a pet rock" (Byrne 1997). Furthermore, Klein and Sorra (1996) found that many different process improvement techniques are in the same paradoxical situation – useful but unused – as TQM. Are managers failing to put intrinsically effective process improvement techniques into action because of a history of failed implementations?

Both managers and scholars need to understand how to implement process improvements successfully. For managers, sustained learning and improvement is a major source of competitive advantage and improved profitability (Stata 1989, de Geus 1988). For scholars, a process improvement initiative substantially changes the physical structure and behaviors of an organization. A deeper understanding of the dynamics of implementing process improvements would contribute to the field of organizational change as a whole.
1.2 Current Theory

Two groups of scholars have developed widely different bases – one physical and one behavioral – for their theories of how to implement change successfully within an organization.

Industrial engineers, operations researchers, and operations management scholars have typically focused on the physical design of manufacturing and service processes (Chase and Aquilano 1989). The quality movement grew out of statistics (Shewhart 1939, Deming 1986). Reengineering has its roots in information technology and computer science (Hammer and Champy 1993). These theories concentrate on modifying the physical structure of the processes while paying less attention to altering the corresponding organizational behaviors. Michael Hammer, commenting on the technical approach of his best-selling book *Reengineering the Corporation*, said, “I was reflecting my engineering background and was insufficiently appreciative of the human dimensions. I’ve learned that’s critical” (White 1996).

In contrast, organizational and management scholars have primarily paid attention to the behavioral aspects of how to implement change successfully (for overviews see e.g. Van de Ven and Poole 1995; Huber and Glick 1993; Kanter, Jick and Stein 1992). Dean and Bowen (1994) show that quality improvement research in the management literature stresses leadership, human resource issues, strategic planning, and other traditional foci of organizational research. Likewise, Hackman and Wageman (1995), working from an organizational theory perspective, analyze the conceptual underpinnings of the quality movement and suggest a research agenda to study its effectiveness. Dean and Bowen (1994:408) write “... management theorists may have gone too far in emphasizing socio-
behavioral over process and technical factors in explaining variation in performance . . . researchers rarely extended their theories to the social and technical aspects of organizational and process design.” In short, just as physical theories largely ignore the behaviors of managers and workers involved in the process, organizational theories generally disregard the physical structure of the process.

Unfortunately, neither the physical nor the behavioral body of theory can explain why organizations fail to implement useful process improvement initiatives successfully. Even though TQM is one of the more widely studied process improvement techniques, Dean and Bowen (1994:393) conclude that "...[TQM] initiatives often do not succeed, but as of yet there is little theory available to explain the difference between successful and unsuccessful efforts." Klein and Sorra (1996) found little theory for other types of process improvements. While the collection of process improvement techniques continues to grow, the knowledge about how to implement those techniques successfully does not.

1.3 Proposed Theory
This thesis offers the beginning of a theoretical framework and a simulation model for understanding how organizations succeed or fail at implementing an inherently effective process improvement initiative. We will tie together elements of the physical and behavioral bodies of theory to create an integrated, interdisciplinary framework. To develop the physical aspect of the framework, we use the basic precepts offered by management science and the founders of the quality movement (Chase and Aquilano 1989, Deming 1986, Garvin 1988, Ishikawa 1985). To construct the behavioral aspect, we rely upon experimental studies of human decision making (Hogarth 1987; Kahneman,
Slovic and Tversky 1982; Plous 1993; Sterman 1989a, 1989b, Paich and Sterman 1993). The main tool for theory development is a system dynamic model capturing the feedback processes within an organization and its environment (Richardson 1991, Masuch 1985, Weick 1979, Forrester 1961). Like the structuration literature (Giddens 1984, 1993; Orlikowski 1992, 1995), we stress the mutual, recursive causal links between technological artifacts – the physical structure – and the organizational and psychological aspects – the behavioral structure. We go beyond the structuration literature by specifying an explicit, operational feedback theory and showing how those feedback processes generate organizational dynamics.

We will see that the physical structure of the process being improved is tightly interwoven with manager’s perception, learning, and allocating resources to the process improvement initiative. We will see how a manager learns over time to allocate scarce resources toward or away from the process improvement initiative. We will then demonstrate, in agreement with the previously mentioned literature, how the dynamics of implementation give rise either to short-term success but long-term failure or to short-term decline but long-term success.
2. Assumptions and Scope

2.1 Signification Behavior Change
While content of the process improvement may be primarily either administrative or technical, the process improvement techniques we are studying require that the participants significantly change their behavior in order for the process improvement to be effective. Examples of this kind of process improvement include TQM, new uses of information technology, and computer-aided design systems.

2.2 Modeling Implementation not Adoption
We further assume, following the terminology of Klein and Sorra (1996), that the formal adoption decision has already been made, and focus on implementation – “…the process of gaining targeted organizational members' appropriate and committed use of an innovation” (Klein and Sorra 1996: 1055).

2.3 The Process Improvement Technique Intrinsically Works
The overall effectiveness of a process improvement initiative is a combination of how well the process improvement technique intrinsically works and how well it is implemented in a given initiative. Since we are interested in how the organizational dynamics affect the implementation of a process improvement technique, we assume that the technique, if properly implemented, actually works and would help the organization. We assume, however, our manager does not know that the technique works. Instead, we will investigate how the she determines the efficacy of the process improvement activities during implementation of a technique.
2.4 Excess Material, Capital Equipment, and Money
In this model, material, capital equipment, and money are in excess and do not constrain the system. Materials and capital equipment are sufficient to meet not only increases in Throughput but also the needs of the process improvement activities (Forrester (1961), Mass (1975), and Lyneis (1980) explore capacity acquisition dynamics. Sterman et al. (1997) and Repenning and Sterman (2000) investigate the interactions between process improvement and capacity.).

2.5 Retain Material and Capital Equipment Dynamics
While we assume that the material and equipment capacity aspects can be eliminated from the model, we will retain their underlying dynamics within the model. Machines will wear out, become obsolete, and be replaced. Our manager will have to expend resources to install, calibrate, test, and maintain these new and repaired machines. This machine turnover process – along with other processes affecting the capability of the system – will be modeled. That is, equipment and materials characteristics will affect the Process Throughput and Process Capability sectors within the model.

2.6 Manager Allocates Scarce Resources
Resources (personnel), however, will be fixed and scarce. In the case studies from which this model is based (Repenning and Sterman 2000), managers did not have the authority to hire additional workers during the process improvement initiative.

Our manager will decide how to allocate these scarce resources to meet goals within the system. She will translate exogenously specified orders and improvement goals into a Throughput, Yield, and resource allocation goals within the system. And, most
importantly, she will determine how many personnel resources to allocate to the process improvement initiative and for how long.
3. Sectors

3.1 Sector Overview
In this chapter, we outline our model at high level, so we can more easily understand how the model fits together. We have broken down the model into five sectors (see Figure 1).

In our hope to build an integrated, interdisciplinary model, we have included sectors that are grounded in the physical and behavioral theories. From the physical side, we have included the following two sectors: Process Throughput and Process Capability. In Chapter 4, we will look at the detailed mathematical structure of the physical sectors and their dynamic implications. From the behavioral side, we have included the following three sectors: Perception, Learning, and Resource Allocation. In Chapter 5, we will add the mathematical structure of these three behavioral sectors to the physical model. Taken together, these five sectors form a model that is the beginning of an answer as to why organizations fail to successfully implement inherently useful process improvement techniques.

Again, the Process Improvement Model consists of five sectors:

1. Process Throughput
2. Process Capability
3. Resource Allocation
4. Perception
5. Learning

3.2 Process Throughput Sector
A process is the series of activities that converts inputs into desired outputs (Garvin 1995a, 1995b). The outputs of a process can be products or tasks. A manufacturing
process converts raw materials into finished products. A product development process converts customer requirements into completed product designs.

Throughput is defined as the amount of work done correctly by the organization in the process modeled. The Process Throughput Sector multiplies Resources to Work from the Resource Allocation Sector by Yield from the Process Capability Sector to get Throughput (see Figure 1). During the process improvement initiative, our manager tries to maintain or increase Throughput given scarce Resources.

3.3 Process Capability Sector

The Process Capability sector captures how effectively the organization works. In our model, the key measure of organizational capability is Yield, the ratio of work done correctly to the total work done. The source of Yield is Problems, also known as ‘root causes’ in the quality literature (Ishikawa 1985). Problems are features of the process, either physical or behavioral, that cause Defects to be generated and decrease Yield. For example, within a paint shop in a manufacturing operation studied by Repenning and Sterman (2000), some products were produced with small scratches. Correcting these defects required repainting. The Problem generating the flow of Defects was found to be employees whose wrist watches, jewelry, or belt buckles scratched the work as they handled parts.

Our manager allocates Resources to Improvement to the process improvement initiative to increase Yield. The Process Capability Sector takes in Resources to Improvement from the Resource Allocation Sector and output Yield.
### 3.4 Resource Allocation Sector

As mentioned in Section 2.6, we have assumed the Resources in the system are fixed and scarce. The Resource Allocation sector captures how our manager decides to distribute Resources to meet the competing demands of Throughput and process improvement goals. The Resource Allocation Sector takes in Learned Productivity of Work and Learned Productivity of Improvement from the Learning Sector. The Resource Allocation Sector outputs Resources to Work for the Process Throughput Sector and Resources to Improvement for the Process Capability and Perception Sectors.

### 3.5 Perception Sector

We have assumed the process improvement technique works. We have not, however, assumed that our manager knows this. Instead, during implementation, she must figure out how effective the process improvement technique is at improving the Throughput.

Our manager determines this efficacy by observing changes in Throughput and Resources to Improvement over time and calculating the perceived productivities of doing work and improving the process. The Perception Sector takes in Throughput from the Process Throughput Sector and Resources to Improvement from the Resource Allocation Sector and outputs the Perceived Productivity of Improvement.

### 3.6 Learning Sector

In the learning sector, our manager updates her beliefs about the productivity of doing work and improving the process. The Learning Sector takes in the Perceived Improvement Productivity and outputs the Learned Improvement Productivity and Learned Work Productivity to the Resource Allocation Sector.
Figure 1. Gray boxes indicate the five sectors in the model. Italic type indicates information or materials flowing between these sectors.
4. Physical Model

In this section, we develop the detailed equations for physical side of the model.

4.1 Process Throughput Sector Equations

A process is characterized by three rates of output. *Gross Process Throughput* is the rate at which the process converts inputs to outputs – either desired or undesired. *Gross Process Throughput* is the product of *Productivity of Work* and *Resources to Do Work*:

Eq 1. \[ GPT = \pi_w R_w \]

*Throughput* is the rate at which inputs are converted into desired outputs. *Yield* is the ratio of desired outputs to total outputs. Thus, *Throughput* is *Gross Process Throughput* times *Yield*:

Eq 2. \[ T = GPT \cdot Y = \pi_w R_w Y \]

*Defect Rate* is the rate at which inputs are converted into undesired outputs – *Defects* (Schneiderman 1988). In manufacturing, a part is that is outside the tolerances is a *Defect*. In product development, a CAD drawing that specifies the correct dimensions, tolerances, and materials for a part but the part is too costly to manufacture is considered a *Defect*. *Defect Rate* is *Gross Process Throughput* times the complement of *Yield*, *Defect Fraction*:

Eq 3. \[ DR = GPT \cdot (1 - Y) = \pi_w R_w (1 - Y) = \pi_w R_w f \]

So, *Gross Process Throughput* is the sum of *Throughput* and *Defect Rate*:

Eq 4. \[ GPT = T + DR \]
Figure 2. The relationship among Gross Process Throughput, Throughput, and Defect Rate expressed in the form of a causal loop diagram (Forrester 1961, Richardson and Pugh 1981, Richardson 1991, Weick 1979). Adapted from Repenning and Sterman (2000).

We have eliminated cycle time, the average time it takes to manufacture a product or complete a design task, from the Throughput Sector. We have assumed that cycle time is much shorter than most other time constants in the model, so changes in cycle time will not affect the dynamics of the model. This simplifying assumption will make the analysis of our model more tractable.

4.2 Process Capability Sector Equations

4.2.1 Yield and Problems
In the Process Throughput Sector, Yield was the ratio of desired outputs to total outputs. Yield, thus, describes the capability of an organization, how much work it can do correctly and effectively. But what is the source of Yield? What is the source of capability of an organization? And, how, with process improvement, does it change over time?

To model the relationship between Problems and Yield, we assume a linear relationship:
Eq 5. \[ Y = -(Y_{\text{max}} - Y_{\text{min}}) \frac{P_{\text{Total}}}{M} + Y_{\text{max}} \]

The *Maximum Number of Problems*, \( M \), is maximum number of *Problems*, \( P \), possible in the system. When *Problems* equals the *Maximum Number of Problems*, the *Yield* is at the *Yield Minimum*. And, when *Problems* are zero, the *Yield* is at the *Yield Maximum*. Between these two extremes, as *Problems* increases, *Yield* decreases. See Figure 3.

![Yield as a Function of the Ratio of Problems to Maximum Number of Problems](image)

**Figure 3.** *Yield* as a linear function of the ratio of *Problems* to *Maximum Number of Problems*.

### 4.2.2 Changes in Organizational Capability

How does the capability of an organization change over time? That is, how does the stock of *Problems* change over time with the process improvement initiative?

Two key flows – the rate of *Problem Introduction Rate* and the rate of *Problem Elimination Rate* – change the stock of *Problems* over time.
Problems are introduced as equipment ages and wears, as employees leave the company taking valuable knowledge with them, and as changes in products, processes, or customer requirements create conflicts with existing procedures, skills, and equipment.

The Problem Introduction Rate is defined as:

\[ PIR = \frac{(M - P)}{\tau_E} \]

Where \( M \) is \textit{Maximum Number of Problems} as before, and \( \tau_E \) is the \textit{Time Constant Due to Entropy}. When the Problems level is near zero, the Problem Introduction Rate is high. Conversely, when the Problems level is near the Maximum Number of Problems, the Problem Introduction Rate is low. That is, when the system is more capable (low Problems), there are more things to go wrong, so more things do go wrong, and Problems increases at a relatively higher rate. Conversely, when the system is less capable (high Problems), there are fewer things to go wrong, so fewer things do go wrong, and relatively lower rate.

Problems are eliminated through the improvement process. Workers document problems, diagnose the underlying causes, experiment to solve the problems, and implement solutions through adjustments to equipment, training, and procedures. To eliminate the problems in the paint shop example, employees began wearing gloves to cover watches and rings and aprons to cover their belt buckles.

Schneiderman (1988) studied the rate of process improvement – Problem Elimination Rate – in operations-focused improvement efforts (principally TQM). He found that “...Any defect level, subjected to legitimate QIP [Quality Improvement Process] decreases at a constant [fractional] rate.” To be consistent with the model and to
distinguish *Problems* (P) from *Defects* (D), we call Schneiderman’s defect level *Problems*. Schneiderman translated this observation into a first-order differential equation describing the number of *Problems* over time:

\[
\frac{dP}{dt} = -\frac{P}{\tau_i}
\]

This model is called the Half-Life Model because the time required for the *Problems* level to fall by fifty percent is constant. The Half-Life Model is a typical specification of improvement in the operations literature.

The Half-Life Model brings together three key concepts. First, it captures the diminishing returns of improvement – as the process improves it becomes tougher and tougher to improve the process. Workers resolve those *Problems* that are easier to solve and have a greater impact on the *Yield* of the process. In turn, they leave tougher and less significant *Problems* for later. Second, the parameter \( \tau_i \) depends on the process being improved and type of initiative being implemented. This parameter realistically recognizes complexity differences between business processes such as manufacturing and product development. Third, the *Problems* level is also the complement of process capability. As *Problems* are eliminated, the organizational capability increases.

While Schneiderman’s Half-Life Model effectively captures many properties of process improvement, it does not address how resources allocated to improvement affect the dynamics of process improvement. That is, Eq. 7 does not include *Resources to Improvement*, so even as *Resources to Improvement* varies, the *Problem Elimination Rate* does not. We will extend the Half-Life Model by explicitly modeling how the level of
Resources to Improvement affects the Problem Elimination Rate. We extend the Half-Life Model to include the following two effects of Resources to Improvement:

1. the effect of the absolute amount of Resources to Improvement
2. the effect of time-varying Resources to Improvement

First, to extend Schneiderman’s Half-Life model, we note that the Problem Elimination Rate is proportional to the amount of Resources to Improvement. The following Resource Limited Rate equation captures the effect of the absolute amount of Resources to Improvement:

Eq. 8 \[ \frac{dP}{dt} = \left( \frac{P}{M} \right) R_{i} \pi_{I_{\text{total}}} \]

Because P is still in the Resource Limited Rate equation above, we still have the effect of diminishing returns to improvement; the Problem Elimination Rate is proportional to P.

We no longer have the parameter \( \tau_{I} \); instead, we now have Total Improvement Productivity \( \pi_{I_{\text{total}}} \) – the number of Problems solved per unit of Resources to Improvement.

Second, we extend the Half-Life Model to include the effect of time-varying Resources to Improvement. If, in Eq. 8, the Resources to Improvement were instantaneously doubled, the Problem Elimination Rate would immediately double as well. The Problems level would immediately decline. The Yield would immediately increase. In the real world, however, if Resources to Improvement were increased, Yield would not immediately increase. Instead, it would take time before Problems would decrease and Yield would increase. Workers need to use these additional hours to diagnose and solve problems and implement their solutions. Fortunately, we can solve this challenge by explicitly
modeling each of the three stages of process improvement. We divide *Problems* in three new substocks and their corresponding outflow rates:

<table>
<thead>
<tr>
<th>Stock Number (n)</th>
<th>Stock</th>
<th>Stock Limited Outflow Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Undiscovered Problems</td>
<td>Diagnose Problems</td>
</tr>
<tr>
<td>2</td>
<td>Diagnosed Problems</td>
<td>Solve Problems</td>
</tr>
<tr>
<td>3</td>
<td>Solved Problems</td>
<td>Implement Solutions</td>
</tr>
</tbody>
</table>

For each stock, we define a characteristic time constant to represent the minimum time it takes to diagnose a problem, solve a problem, or implement a solution. For simplicity, in this model, we assume all of these minimum time constants are equal. We can explicitly articulate the Stock Limited Rate for each of the flows as follows:

\[
\text{Eq. 9} \quad \frac{dP_n}{dt} = -\frac{P_n}{\tau_{I_n}}
\]

where \( P_n \) is one of the three substocks, and \( \tau_{I_n} \) is the characteristic time constant.

Now that we have divided the *Problems* stock into three substocks, we need to revise Eq. 8, the Resource Limited Rate equation, to include two new effects of having multiple substocks:

1. creating an *Improvement Productivity* for each outflow
2. allocating Resources to Improvement among the outflows

First, we get rid of *Total Improvement Productivity* and replace it with *Improvement Productivity*, \( \pi_{I_n} \), for each of the outflows. And, just as with the *Improvement Time Constant*, we will simplify the model by making *Improvement Productivities* for each of
the outflows equal. Second, we need to allocate Resources to Improvement among the outflows. While we have assumed that the Improvement Productivities for each of the outflows are equal, the size of the Problems substocks will differ at any given time, so, naturally, we should allocate more Resources to Improvement to the stock with a greater number of Problems. We allocate Resources to Improvement for each of outflow rates by calculating the Weight on Resources to Improvement for each of the Problem substocks as follows:

Eq. 10 \[ W_n = \frac{P_n}{\pi_{I_n}} \]

A larger share of Resources to Improvement is given to the outflow from substock with more Problems and lower Improvement Productivity. We then use an \( \text{US}/(\text{US}+\text{THEM}) \) allocation rule (Kalish and Lillien 1986) to divide Resources to Improvement among the three outflows:

Eq. 11 \[ R_{I_n} = R_J \frac{W_n}{\sum_n W_i} \]

We revise Eq. 8 to be:

Eq 12. \[ \frac{dP_n}{dt} = -\left( \frac{P_n}{M} \right) R_{I_n} \pi_{I_n} \]

We then take the minimum of the Stock Limited Rate and the Resource Limited Rate, Eq. 9 and Eq. 12, to get the extended-Half Life Model:

Eq. 13 \[ \frac{dP}{dt} = \min \left( -\left( \frac{P_n}{M} \right) R_{I_n} \pi_{I_n}, -\frac{P_n}{\tau_{I_n}} \right) \]
4.2.3 Distinction Between Defect Correction and Defect Prevention

Explicitly articulating the stock and flow structure of processes gives insight into the importance of the distinction between defect correction and defect prevention. One Problem creates a continual inflow of Defects, forever reducing Throughput unless each and every defect is corrected. When a Problem is corrected, however, the Defect Rate is forever reduced. A fundamental contribution of the founders of the quality movement...
was to recognize the distinction between correcting defects that have already been produced and preventing them from occurring (Deming 1986). The challenge of process improvement is to shift attention from reducing the stock of Defects to reducing the stock of Problems.

4.3 Optimal Throughput and Optimal Yield

The two physical sectors – Process Throughput and Process Capability – need Resources to increase Throughput and Yield, respectively. Previously, we assumed that Resources were fixed and scarce. This scarcity gives rise to an optimum resource allocation between Process Throughput and Process Capability to determine Optimal Throughput and Optimal Yield.

We determine these optimal conditions not in a dynamic situation but, rather, in a steady-state one. That is, at equilibrium, by definition, the three Problems substocks are not changing. The Problem inflow and outflow rates are not changing. The rate of Problem Introduction Due to Entropy is equal to the Rate of Implementing Solutions. Problems do not change. Yield does not change.

The Resource Constraint is:

\[ R = R_w + R_I \]

By Little’s Law and assuming the equilibrium Problem Elimination Rates are resource limited and not stock limited, we can solve for the equilibrium Total Problems in all the Problem substocks as a function of Resources to Improvement:

\[ P_{\text{Total}} = \frac{zM}{z + \frac{\pi_I \tau_\ell R_I}{zM}} \]
Substituting Eq. 15 into the Yield Equation (Eq. 5) and the resultant into the Throughput Equation (Eq. 2) and substituting \( R - R_I \) for \( R_w \) from the Resource Constraint (Eq. 14), we get the **Throughput** as a function of **Resources to Improvement**:

\[
T = (R - R_I)\pi_w \left[ \frac{-z(Y_{\text{Max}} - Y_{\text{Min}})}{(z + \frac{\pi_I\tau_E R_I}{zM})} + Y_{\text{max}} \right]
\]

Setting the derivative of Eq. 16 equal to zero and solving for \( R_I \), we get the **Optimal Resources to Improvement**:

\[
R_I^* = -\frac{zYM_{\text{Max}} - \sqrt{YM_{\text{Max}}(Y_{\text{Max}} - Y_{\text{Min}})(z^2M + R\tau_E\pi_I)}}{YM_{\text{Max}}\pi_I}
\]

Substituting Eq. 17 back into the Yield (Eq. 5) and Throughput (Eq. 2) equations, we get the **Optimal Yield** and **Optimal Throughput**, respectively

\[
Y^* = \left( \frac{-z(Y_{\text{Max}} - Y_{\text{Min}})}{z - \frac{YM_{\text{Max}} - \sqrt{YM_{\text{Max}}(Y_{\text{Max}} - Y_{\text{Min}})(z^2M + R\tau_E\pi_I)}}{YM_{\text{Max}}}} - Y_{\text{Max}} \right)
\]

\[
T^* = \pi_w (R - R_I^*)Y^*
\]

Figure 5 shows a contour plot of **Throughput** as a function of **Resources to Work** and **Resources to Improvement**. The **Initial Throughput** and **Optimal Throughput** are indicated along the Resource Budget Constraint of 1000 worker-hours/day. The Resource-Throughput hill, Figure 6, shows a steep gradient between the **Initial Throughput** and **Optimal Throughput**.
 Iso-Throughput and Resource Budget Constraint

Figure 5. The intersection of the Resource Constraint Curve and the Iso-Throughput lines gives the Initial and Optimal Resources to Improvement, Initial Optimal Resources to Work, and Initial and Optimal Throughput.
Throughput Based on Resources to Improvement
(Throughput (Resources Constrained to 1000 worker-hours/day))

Figure 6. The Resource-Throughput Hill. For a given Resources (1000 worker-hours/day), the Throughput curve is shown. Initial and Optimal Throughput are shown. Note the steep gradient from Initial Throughput to Optimal Throughput as Resources to Improvement is increased.
5. Behavioral Model

In the Chapter 4, we learned that the physical system has an *Optimal Throughput*. But how does our manager move toward this *Optimal Throughput*? And, how does the challenge of implementing the process improvement interact with this optimization? In Chapter 5, we will look at how our manager perceives, learns, and acts on the system to increase the *Throughput* of the process while implementing the process improvement initiative.

5.1 Resource Allocation Sector

Repenning (forthcoming) begins to answer our second question – how does our manager implement the process improvement initiative. To do so, he distinguished between two pressures – normative and instrumental – that form an organization’s *Commitment* to the process improvement initiative. In this model, we will translate Repenning’s *Commitment* variable into our *Resources to Improvement* variable. In this chapter, we extend Repenning’s analysis. We will show how normative and instrumental pressures determine how our manager allocates scarce resources to the competing demands of getting work done and improving the process.

5.1.1 Instrument and Normative Pressure Distinguished

The motivation and commitment literatures discuss two types of pressures – normative and instrumental. Scholl (1981) distinguishes between commitment that stems from instrumental beliefs – the assessed expectancy of an outcome given an action – and other sources of commitment – mainly identification with and compliance to an organization’s subjective norms. Similarly, Weiner (1982) contrasts "calculative" commitment, produced by expectancy, and "normative" commitment, generated by non-instrumental...
sources. Steers and Porter (1991:108) conclude, "...the question of motivation comes down to the complex interaction between the ‘push’ forces within the person and the ‘pull’ forces within the environment."

5.1.2 Normative Pressure
While there are numerous "non-instrumental" sources of commitment and, thus, forces to change Resources to Improvement, for the purposes of our model, we will aggregate them into one type of pressure – normative. Specifically, we assume that, upon implementing a process improvement technique, our manager sets a target for the improvement process, the Resources to Improvement Goal, $GR_I$. With this goal in mind, our manager determines the difference between the current Resources to Improvement and the Resources to Improvement Goal to get the Resources to Improvement Gap. Our manager then takes actions to close this gap. She may publicly ally herself with the use of the process improvement, institute reward systems based on usage, or promote compliance via direct surveillance (see Meyer and Allen 1997 for others). These actions increase the Desired Resources to Improvement and, in turn, increase the Resources to Improvement (see Figure 7). For the Normative Pressure loop, the rate of change of the Desired Resources to Improvement is the Normative Change in Desired Resources to Improvement as follows:

$$\frac{dDR_{\text{norm}}}{dt} = \text{Max} \left( \frac{GR_I - R_I}{\tau_{\text{Norm}}}, 0 \right)$$

We have included the max function to keep the Normative Change in Desired Resources to Improvement positive even if Resources to Improvement exceeds the Resources to Improvement Goal. That is, if the workers utilize more Resources to Improvement than
the manager desires, she will not use normative pressure to cut back their improvement efforts.

Figure 7. Manager tries to improve the process by setting the Desired Resources to Improvement, calculating the difference between the desired and actual, and trying to close this gap. Adapted from Repenning and Sterman (2000).

5.1.3 Instrumental Pressure
While implementing the process improvement technique, workers must still get work done. Products must be designed. Widgets must be manufactured. Our manager
articulates her goal for how much work to get done, the Throughput Goal. Our manager then determines the difference between the Throughput Goal and the Indicated Throughput to get the Throughput Gap. Management and workers attempt to close this gap by:

1. Working Harder: increase the Resources to Work
2. Working Smarter: increase the Resources to Improvement, improve the process capability, and increase the Yield

Both of these options form goal seeking feedback loops (negative or balancing), attempting to close the Throughput Gap by raising the Throughput to meet the Throughput Goal.

5.1.4 Working Harder: the Symptomatic Solution to Closing the Throughput Gap
Faced with a Throughput Gap, our manager can close it by expanding production capacity, reworking defective output, or using existing capacity more intensely. Each of these options forms a balancing feedback loop (negative) whose goal is to eliminate the Throughput Gap by raising Throughput toward the Throughput Goal.

First, our manager can expand production capacity by hiring more workers and purchasing additional plant and equipment, boosting Gross Throughput. However, expanding capacity takes time, is costly, and is generally not an option for managers responsible for day-to-day operations. In Chapter 2, we have assumed that the manager cannot increase the equipment capacity of plant through capital expansion. Increasing resources was beyond the authority of the managers in the improvement programs in the cases studied by Sterman and Repenning (2000).
Second, our manager can allocate resources to correcting Defects, creating the balancing Rework loop. In manufacturing, workers might repaint scratched parts. In product development, engineers might redesign faulty drawings. Initially, we will assume that rework is not a possibility.

Third, to increase Throughput, our manager can have workers use existing resources more intensely. Workers would then eliminate breaks, cut down on absenteeism, and, most importantly, reduce efforts on improving the process. This option creates the balancing Work Harder loop (see figure 8).

Each of the three symptomatic improvement feedback loops outlined above can close the Throughput Gap but only at significant and recurring cost. Each time a Defect occurs, the manager must have the workers Work Harder to complete another task or produce another product.

5.1.5 Working Smarter: the Fundamental Solution to Closing the Throughput Gap
A more effective, more fundamental way to close the Throughput Gap is to eliminate the Problems that decrease Yield and generate Defects (Deming 1986). Process improvements efforts create the balancing Working Smarter loop (see Figure 8) that closes the Throughput Gap by permanently eliminating Problems that generate Defects.

To making such fundamental improvements, our manager must train workers in improvement techniques, release those workers from their normal responsibilities so they may participate in improvement activities, and give them the freedom to deviate from established routines so they may experiment with potential solutions.
While the fundamental solution – process improvement – eliminates *Problems* forever and increases *Yield* permanently (setting aside the effects of the *Problem Introduction Rate* for the moment), process improvement works against many cognitive biases. Process improvement is risky, takes time, and, frequently, is intangible. Moreover, managers must commit to a process improvement effort that they do not, a priori, whether it works.

![Diagram](image)

**Figure 8.** Our Manager can close the *Throughput Gap* either by increasing *Resources to Improvement*, increasing the *Yield*, and increasing *Throughput* or by increasing *Resources to Work* and increasing *Throughput*. Adapted from Repenning and Sterman (2000).
5.1.6 The Vicious and Virtuous Effects of Scarce Resources

Workers have limited time to allocate between doing work and improving the process. And, since this time, Resources, is fixed and scarce, the loops are coupled. Finite and scarce resources create two new feedback loops – Vicious and Virtuous (see Figure 9). These Vicious and Virtuous loops are positive feedback loops, reinforcing whatever behavior current dominates the system.

Successful process improvement increases Yield that, in turn, increases Throughput. As the Throughput Gap falls, workers have more time to devote to solving Problems, leading to still more improvement and still higher Yield and Throughput. The reinforcing loop act virtuously – increasing the capability of the organization over time.

Conversely, if Resources are shifted away from process improvement and toward Throughput, Throughput immediately increases. But, in time, as Resources to Improvement decreases, Problems increase. Yield falls. Throughput falls. Even more Resources must be allocated to Resources to Work to increase Throughput. This reinforcing loop acts viciously – decreasing the capability of the organization over time.

For example, deferring preventive maintenance to repair unexpected equipment breakdowns can lead to more breakdowns and still greater pressure to reassign maintenance mechanics from preventive to reactive work (Carroll, Marcus and Sterman 1997).
5.1.7 Deciding to Work Harder or Work Smarter

Instrumental motivation focuses on closing the Throughput Gap and increasing the Throughput of the system. Our manager can either work harder – increase the Desired Resources to Work – or work smarter – increase the Desired Resources to Improvement by evaluating two things. First, she looks at the Throughput Pressure on the system. Second, she assesses the relative productivities of these two activities.

First, our manager determines the Throughput Pressure on the system by determining the Effect of Throughput Gap on the Throughput Gap and then multiplying this by...
Throughput Pressure at No Throughput Gap \((TP_o)\) to get the Throughput Pressure \((TP)\) (see Figure 9). This relationship is expressed in Eq. 21 as follows:

\[
Eq. 21 \quad TP = TP_o \cdot Effect_{TG}(TG)
\]

Effect of Throughput Gap on Throughput Pressure

Figure 10. Logistic Function of Effect of Throughput Gap on Throughput Pressure. When Throughput equals Throughput Goal, Throughput Gap is zero, and the Effect of Throughput Gap is 1.0.

Looking carefully at Figure 10, we see that, when the Throughput Gap is zero, the Effect of Throughput Gap is still 1.0. This means that even if there is no Throughput Gap, the Throughput Pressure is Throughput Pressure at No Throughput Gap or 0.025 in the base
case. Our manager will continue to try to improve the system even if there is no
Throughput Gap. This effort is equivalent to climbing the Resource-Throughput hill
toward the Optimal Throughput.

Second, our manager determines the Instrumental Pressure, the pressure to change the
resource allocation based on the difference the Learned Work Productivity and the
Learned Improvement Productivity divided by the Work Productivity. This relationship
is shown in Eq. 22.

\[ IP = \frac{L\pi_w - L\pi_I}{\pi_w} \]

Our manager then multiplies the Throughput Pressure by the Instrumental Pressure to
get the Pressure on Work and Pressure on Improvement.

\[ P_w = IP \cdot TP \]

\[ P_I = IP \cdot TP \]

We then model the Instrumental Change in Desired Resource to Work and Instrumental
Change in Desired Resources to Improvement as an anchor and adjustment:

\[ \frac{dDR_{iw}}{dt} = \frac{DR_I \text{Max}(\text{Min}(P_I, range),-range)}{\tau_{inst}} \]

\[ \frac{dDR_{iw}}{dt} = \frac{DR_I \text{Max}(\text{Min}(P_I, range),-range)}{\tau_{inst}} \]

where range is the minimum and maximum change possible.

Within this instrumental resource allocation scheme, our manager will allocate more
Resources to the activity that is more productive. She will also allocate Resources at a
rate based on the *Throughput Pressure* and the relative difference between the productivity of work and improvement activities. And, significantly, our manager will try to improve the system regardless of the desire to implement the process improvement technique. That is, as our manager attempts to increase *Throughput* by allocating *Resources* to the activity that she learns is more productive, she will try to climb the Resource-Throughput hill (see Figure 6) toward the *Optimal Throughput*.

### 5.1.8 Resource Allocation Sector Equations

With the *Desired Resources to Work* and the *Desired Resources to Improvement* from the combined effects of the normative and instrumental feedback loops, we need to divide the *Total Resources* between the competing activities of work and improvement. For this we use an US/(US+THEM) structure as follows:

Eq. 26 \[ R_i = \frac{DR_i}{(DR_i + DR_w)} R \]

Eq. 27 \[ R_w = \frac{DR_w}{(DR_i + DR_w)} R \]

where \( R_i \) is the Resources to Improvement, \( R_w \) is the Resources to Work, \( R \) is the Total Resources.

### 5.1.9 Optimizing Throughput with Perfect Process Information

In Chapter 4, we developed that Physical Model of the process. So far, in Chapter 5, we have developed how our manager decides to implement changes in the Resource Allocation Sector given learned productivities and *Throughput Pressure*. If, for the moment, we assume that our manager can know these productivities immediately and that there is no *Throughput Gap*, so that *Throughput Pressure* equals *Throughput*.
Pressure at No Gap, we will understand how she might climb this Resource-Throughput Hill (see Figure 6) toward the Optimal Throughput.

To know the productivities immediately, our manager must know:

1. Resources to Work and Resources to Improvement without delay
2. Yield and Throughput without delay
3. the underlying structure – the exact functional form – of the system perfectly and must have the ability:

4. to combine this information precisely
5. to calculate the partial derivative of Throughput with respect to Resources to Work and Resources to Improvement

If our manager has these abilities and information, we will call the situation having “perfect process information.”
Perfect Process Information:
Learned Improvement Productivity vs Learned Work Productivity

![Graph showing Learn Productivity vs Learn Work Productivity](image)

Figure 11. Perfect Process Information: Learned Improvement Productivity vs. Learned Work Productivity. Note that Learned Improvement Productivity starts at 6.75 units/(worker-hour), much higher than Learned Improvement Productivity, which starts at 0.71 units/(worker-hour). The process improvement initiative is seen as highly productive.
Figure 12. Perfect Process Information vs. Initial for Fraction of Optimal Throughput. For Perfect Process Information, the Fraction of Optimal Yield dips down and then rises to the optimal level. This dip is the “worse before better” mentioned in the literature.
Figure 13. Perfect Process Information v. Initial for Fraction of Optimal Yield. Note, for the Perfect Process Information, the Fraction of Optimal Yield is initially flat because of the third-order delay in the Process Capability sector. Later, the Fraction of Optimal Yield rises to 1.0 – the optimal level.

If our manager has perfect process information about the system, she can quickly climb the Resource-Throughput hill and find Optimal Throughput and Optimal Yield. Initially, with perfect process information, our manager would learn that improvement is far more productive than work. Learned Improvement Productivity starts at 6.75 units/(worker-hour) while Learned Work Productivity starts at 0.71 units/(worker-hour) (see Figure 11).
And, as our manager invests in highly productive improvement at the expense of work, *Throughput* falls (see Figure 12). *Yield* is initially flat due to the third-order delay in the Process Capability Sector (see Figure 13). Later, *Yield* rises as the investments in process improvement come to fruition (see Figure 13); *Throughput* rises out the “worse before better” dip (see Figure 12). *Learned Improvement Productivity* falls to meet the rising *Learned Work Productivity* (see Figure 11). When these two variables are equal – that is, when, with perfect process information, our manager has equated the two partial derivatives of *Throughput*– the system reaches the *Optimal Throughput* and *Optimal Yield*.

### 5.2 Perception

In instrumental structure in the previous section, we assumed that our manager allocates *Resources* to work or improvement based on which activity increases *Throughput*. But how does our manager determine the productivities of these two activities to make this decision?

#### 5.2.1 Bounded Rationality and Assessment of Productivities

Economists might model our manager taking partial derivatives of, say, *Throughput* with respect to *Resources to Improvement*, as we did in section 5.1.9. The ability to take these partial derivatives assumes that our manager can and must do the following:

1. spend time observing and measuring all potential confounding variables
2. remember these variables over time
3. know the underlying function that describes the system
4. compute the partial derivative of this underlying function, holding all other confounding variables constant and accounting for measurement and observation noise
In short, in most cases a partial derivative-like model is beyond the scope of human perception, memory, and processing. In Section 5.1.9, we defined a manager with a certain set of information and capabilities as having perfect process information. In this section, we will define our manager, limited by the perception and learning processes outlined above, as being boundedly rational.

5.2.2 The Differential
In place of the partial derivative, we purpose a new descriptive, behavioral theory of how people measure rates of change in two variables – the differential. The differential is a more reasonable, less complex, descriptive, and boundedly rational process of calculating productivities. Our manager takes the differential of the instrumental variable she is interested in, in this case Throughput, with respect to the independent and presumably causal variable, Resources to Improvement. She cannot and does not observe, measure, remember, or compute the effects of all confounding variables and noise. She simply sees how Throughput changes as Resources to Improvement changes. She does not know the underlying functional form; she assumes a linear relationship between the independent variable, Resources to Improvement, and the dependent one, Throughput. These realistic cognitive limitations will lead to reasonable – and sometimes severely mistaken – biases in the perception of the productivity of work and improvement.

Within system dynamics and behavioral simulation models, the TREND function has been used to model how people form expectations about the growth rate of a quantity adaptively from the recent growth rate of the input variable. Sterman (1987) tested the TREND function in two different domains and showed that it was an appropriate behavioral representation of how people form expectations. The TREND function
describes the process by which people actually perceive and learn about quantities rather than demonstrating how people should act to maximize or optimize utility. The TREND function addresses the fact that it takes time for people to collect and analyze data and to change their underlying beliefs about the data.

Just like the TREND function, the differential is descriptive not normative. It describes the process by which managers determine how quickly one quantity changes with respect to another quantity over time. As a description, the differential will include limitations on our manager’s cognitive capacities—biases, misinterpretations, delays, and distortions.

The differential function takes in two variables over time and outputs the rate of change of one of those variables with respect to the other overtime. The differential function will take into account extreme conditions when one variable barely changes with respect to its absolute value. We will use the basic elements of TREND function and extend it to describe how our manager forms perceptions about the productivities of doing work and improving the process. The differential is constructed out of the following four components:

1. Like the TREND function, recent and historical values for each variable are determined
2. The difference between the recent and historical values is taken and divided by the historical time constant
3. The rate of change for each variable is compared to the noise threshold value for that variable
4. One rate of change is divide by the other

First, our manager perceived data over time. She exponentially smoothes in incoming data to get the recent value of both input variables. Smoothing of the input variable does
two things. Our manager needs time to measure the input variables. And, our manager
smoothes the high frequency noise out of a noisy system complicated by measurement
errors. Next, our manager forms her perception of the historical value of the input
variable. She exponentially smooths the recent value. The historical time constant
determines the relevant historical period considered in the perception process.
Equivalently, the historical time constant is the rate at which old information is
discounted.

Second, our manager takes the difference between the recent value and the historical
value of the variable and divides this difference by the historical time constant to get the
rate of change in the input variable, *Difference in Throughput* and *Difference in
Resources to Improvement*. Note, that unlike the TREND function, we do not divide by
the recent measurement of the input variable. We want the derivative of the input
variable with respect to time rather than the growth rate of the input variable. With these
first two steps, we have modeled how our manager forms the differential with respect to
time for each input variable (see Figure 14).

Third, our manager will only act on perceptions of change in data that are above the noise
threshold in a process. Our process has intrinsic noise. Measurement, reporting, and
calculation are all noisy processes. Below a certain noise threshold, our manager cannot
perceive a change. To account for the inability to perceive changes in a noisy process,
we develop a formulation similar to Weber’s Law in psychophysics. A modern
interpretation of Weber’s Law suggests that the brain cannot discriminate below a certain
level, the just noticeable difference. This just noticeable difference is limited by noise in
the nervous system. That is, in order to give reliable signals, the brain favors no signal
rather than false signal. Weber’s law states that the smallest difference in intensity – the just noticeable difference – that can be reliably detected is directly proportional to the background intensity (Gregory 1998). Mathematically, Weber’s Law is represented as:

\[ \Delta I = kI \]

where \( \Delta I \) is the difference in intensity (the just noticeable difference), \( I \) is background intensity, and \( k \) is a proportionality constant.

If we interpret the differential with respect to time as the difference in intensity and the recent value of the variable as the background intensity, we can see that Weber’s just noticeable difference is proportional to the background intensity. Such a statement is complementary to our interpretation. Our manager would have a just noticeable difference in the perception of a change of a variable due to noise. There is noise throughout our system – in the process itself, in the measurement of the inputs and outputs of the process, and in the reporting of these measurements. With this in mind, we construct our equivalent of the Weber’s Law. The Throughput Threshold is the Throughput Threshold Fraction times the Recent Throughput as follows:

\[ thT = thT \cdot T_{Recent} \]

A reasonable value for the Throughput Threshold Fraction is \( 10^{-5} \). This value corresponds to a change of 0.36% in a variable over a year. The Throughput Threshold scales with recent value of the Throughput variable. And, the Difference in Throughput is thresholded as follows to get Perceived Rate of Change in Throughput:

\[ P\Delta T = \Delta T \quad \text{if} \quad \Delta T \geq thT \]

\[ P\Delta T = 0 \quad \text{if} \quad \Delta T < 0 \]
From Eq. 30, above the *Throughput Threshold*, the *Perceived Rate of Change in Throughput* is *Difference in Throughput*. Below the *Throughput Threshold*, our manager perceives no change in the *Throughput*.

*Perceived Rate of Change in Resources to Improvement* is calculated in a similar fashion.

### 5.2.3 Calculating the Perceived Productivities

Once we have determined the differential with respect to time for each variable and compare it to the respective threshold difference, we need to determine the *Perceived Productivity of Work* and the *Perceived Productivity of Improvement*. In this model, we will assume that, because *Yield* and *Work Productivity* can be easily measured and calculated, that the *Perceived Productivity of Work* is:

\[ P\pi_w = \pi_w Y_{recent} \]

But, for the *Perceived Productivity of Improvement*, we will use the differential function. We divide the *Perceived Rate of Change in Throughput* by the *Perceived Rate of Change of Resources to Improvement* to get the *Perceived Change in Throughput given Resources to Improvement*:

\[ P\pi_I = \frac{P\Delta T}{P\Delta R_I} \]

This ratio is similar to the covariation function.

### 5.3 Learning

Once our manager has the *Perceived Change in Throughput given Resources to Improvement*, she must change her underlying beliefs about the system. To model the process of learning how instrumentally useful the process improvement initiative is we
use a modified version of the anchor and adjustment formulation. When modifying the anchor and adjustment formulation, we first need to take into account if the perceived variables changed over time and, if so, by how much, and, second, we need to account for how much change in the causal variable Resources to Improvement occurred.

5.3.1 The Learning Adjustment

If both the Perceived Rate of Change in Throughput by the Perceived Rate of Change of Resources to Improvement changed greater than their respective thresholds (they are both nonzero after threshold functions Eq. 30), we used the Perceived Change in Throughput given Resources to Improvement as the adjustment – this is just the Perceived Rate of Change in Throughput divided by the Perceived Rate of Change of Resources to Improvement (see lower right have quadrant of Eq. 33). But, if either one variable or the other was below its threshold, we need to adjust the anchor according to how the other variable moved (see the upper right and lower left quadrants of Eq. 33). That is, if Perceived Rate of Change in Throughput was below its threshold and Resources to Improvement was increasing, our manager sees that she needs to increase Resources to Improvement to maintain the same Throughput. Therefore, she learns that Learned Improvement Productivity needs to be reduced. Finally, if both variables are below their respective thresholds, we do not change the Learned Improvement Productivity at all (see upper left quadrant of Eq. 33).
5.3.2 The Learning Update Fraction based on Information Content

Second, we need to account for how much change in Resources to Improvement occurred when updating the manager’s belief in the Learned Productivity of Improvement.

Because our manager assumes Resources to Improvement affect Throughput, if she changes Resources to Improvement very little, she should expect very little change in Throughput and update her beliefs very little. So, with this in mind, we assume that the update fraction $u_{cov}$ for the right-hand side of Eq. 33 is proportional to the amount of Recent Resources to Improvement. We model the information content as $\Delta R_t$ times $E$, the Effect of Information in Difference Resources to Improvement on Update Fraction, to get:

\[
\text{Eq. 34 } u_{cov} = \max(E\Delta R_t, u_{cov_0})
\]
That is, as the amount of change in Resources to Improvement increases the $u_{cov}$ increases up to a maximum $u_{cov}^o$. The other quadrant has a fixed update fraction.

Figure 14. Our manager perceives, learns, and acts on the productivity of work and improvement to close the Throughput Gap.
6. The Effect of Normative Pressure on Implementation

6.1 Starting in Equilibrium
With all runs, before implementing the process improvement initiative, our manager perceives the Learned Productivity of Improvement equal to the Learned Productivity of Work. Because of this equality, our manager does not change the resource allocation. The system is in equilibrium. In Figure 20, the Instrumental Pressure is zero – the Learned Productivity of Work equals the Learned Productivity of Improvement.

6.2 The “Worse” in “Worse Before Better”
On day zero, our manager steps up Goal Resources to Improvement Fraction of Optimal Resources to Improvement from the initial to the optimal level for a period called Push Time. During this normative pressure period, our manager increases the Desired Resources to Improvement at exponentially decreasing rate as she closes the gap between Fraction of Resources to Improvement and Fraction of Resources to Improvement Goal. Similarly, Resources to Improvement increases at an exponentially decreasing rate (see Figure 16). This normative increase in Resources to Improvement takes the system out of equilibrium and does three things:

1. with a delay, Yield increases (see Figure 17)
2. immediately decreases Resources to Work due to the resource constraint
3. immediately decreases Throughput (see Figure 15)

First, as Resources to Improvement increases, workers to diagnose more problems, solve more experiments, and implement more solutions. These processes take time. Our manager does not see an immediate payoff. Initially, Total Problems and, thus, Yield stay flat. Later, Yield increases at an increasing rate and this increasing rate increases as well
as previous investments in process improvements come to fruition (see Figure 17).

Overall, this initial investment in process improvement is successfully accelerating capabilities improvement. Second, because Total Resources are constrained, as Resources to Improvement increases, Resources to Work decreases. Third, as Resources to Work decreases while Yield stays flat, Throughput decreases (see Figure 15). This is the “worse” phase in the “worse before better” phenomenon mentioned in the literature. In addition to encouraging the adoption of the process improvement initiative through the normative balancing loop, our manager tries to improve the Throughput of her process. To do this, she evaluates how well an unknown yet potentially effective process improvement technique might increase Throughput. To make this assessment, she evaluates how Throughput changes as Resources to Improvement changes.

In this “worse” phase, as Throughput decreases, the Perceived Rate of Change in Throughput goes negative (see Figure 18). And, as Resources to Improvement increases, the Perceived Rate of Change in Resources to Improvement goes positive (see Figure 19). Our manager takes these two rates together – dividing a positive one by a negative one – to recognize that there is a negative covariation between Throughput and Resources to Improvement during this “worse” period. She perceives that the process improvement initiative decreases the Throughput of her process. Our manager then updates her belief the process improvement initiative; she now thinks that the Learned Improvement Productivity is negative. She believes that the process improvement is not only less productive than work it is also decreases the Throughput of the process. The instrumental loop favors doing more work and less improvement; the Instrumental Pressure goes positive (see Figure 20).
During this “worse” phase, however, the normative loop is much stronger than the instrumental loop. Our manager continues to increase Resources to Improvement despite the negative results from the instrumental loop (see Figure 16).

6.3 Out of the Crisis? Ending Normative Pressure
At the Push End time, our manager decides to end the normative pressure to implement the process improvement initiative. She no longer increases Desired Resources to Improvement based normative pressure. Now, only instrumental pressure can change the Desired Resources to Improvement. Exactly when our manager decides to end the normative pressure will determine what she perceives, believes, and acts on in the system. We will look at six representative cases that illustrate key features of the model and understand how the interwoven dynamics of the process and the manager perceptions, beliefs, and actions determine the success or failure of the process improvement initiative.

6.4 Never Perceived Success
In the first case, our manager ends the normative pressure at 10 days, and the process improvement initiative fails.

When our manager ends the normative pressure, the Normative Change in Desired Resources to Improvement goes to zero. As in the initial “worse” phase, the instrumental pressure favors work over improvement, so Instrumental Change in Desired Resources to Improvement is negative, and Resources to Improvement declines (see Figure 16). After a perception delay, the Perceived Rate of Change in Resources to Improvement stays positive but decreases (see Figure 19).
As Resources to Improvement declines, Resources to Work increases. Yield continues to increase because of previous investments in process improvement (see Figure 17), so Throughput increases (see Figure 15). The process comes out of the “worse” phase of the “worse before better.” Note, that in this case with these parameters and with a sufficiently short Push End time, our manager’s decision to end the normative pressure in turn causes the Throughput to increase immediately. If the normative pressure had continued, the Throughput would have continued to decline. In our first case, Push End 10 days, the Perceived Rate of Change in Throughput goes below the Throughput Threshold Fraction (see Figure 18) and, to our manager, Throughput does not appear to change. At the same time, the Perceived Change in Resources to Improvement goes negative (see Figure 19). So, for a period, our manager does not perceive a positive correlation between the Throughput and Resources to Improvement. Instead, she notes the decrease in Resources to Improvement for perceptually the same Throughput. The Instrumental Pressure remains roughly the same (see Figure 20). Later, in the case of Push End 10 days, the Perceived Rate of Change in Throughput goes positive while the Perceived Rate of Change in Resources to Improvement goes negative (see Figure 18 and 19). Our manager continues to perceive a negative Covariation between Throughput and improvement efforts. The process improvement initiative fails. The Resources to Improvement and Yield go below initial levels (see Figure 16 and Figure 17).

6.5 Perceived Success but Never Learned It
In the second case, Push End 50 days, our manager exerts enough normative pressure to perceive that the process improvement initiative is successful. But, she does not sustain
this normative pressure long enough to learn of this success. Again, the process improvement initiative fails.

As in the Push End 10 days scenario, in the Push End 50 days case, just after the normative pressure ends, the Throughput rises (see Figure 15). As Throughput increases, the Perceived Rate of Change in Throughput, after a perception delay, increases and goes from negative to positive (see Figure 18).

Taking the now positive Perceived Rate of Change in Throughput and the still positive Perceived Rate of Change in Resources to Improvement together, our manager changes her instrumental perception of the process improvement initiative. She now perceives a positive covariation between Throughput and process improvement. Still, this newfound perception is not sufficient to make her belief in Learned Improvement Productivity greater than Perceived Work Productivity. The Instrumental Pressure stays positive (see Figure 20). Our manager continues to allocate Resources toward from work and away from improvement.

Throughput rises for some time (see Figure 21). But, as Resources to Improvement declines, Yield falls (see Figures 22 and Figures 23). In time, Throughput falls (see Figure 21). The process improvement initiative fails.

6.6 The Prebifurcation Case
In the third case, the prebifurcation case (Push End 135 days), the process improvement initiative fails.

Just as before, the following is true:

1. Resources to Improvement is rising due to normative pressure and despite the instrumental pressure (see Figure 16)
2. *Resources to Work* is falling due to normative pressure and because the instrumental pressure

3. *Throughput* is falling (see Figure 15)

4. *Yield* is increasing at an increasing rate (see Figure 17)

But, in this case the perception that the process improvement works continues until she changes her belief in it. With a new belief that the process improvement initiative is instrumentally effective – *Instrumental Pressure* goes negative (see Figure 20), our manager allocates *Resources* away from work and toward improvement (see Figure 16).

At the same time our manager begins to allocate more *Resources* toward improvement, she finally to perceive the decline of *Resources to Improvement* that was initiated when the normative pressure ended and the instrumental pressure favored work over improvement. The *Perceived Rate of Change in Resources to Improvement* goes negative (see Figure 19). Combining the recently positive *Perceived Rate of Change in Throughput* (see Figure 18) and the now negative *Perceived Rate of Change in Resources to Improvement* (see Figure 19), she perceives a negative covariation between *Throughput* and process improvement. Her perception of the process improvement initiative oscillates quickly. She changes her belief in the process improvement initiative. And, the *Perceived Improvement Productivity* goes below the *Perceived Work Productivity*. Just after she finished increasing the allocation of *Resources* to the process improvement, she changes her beliefs and her *Resource* allocation. But, in this prebifurcation case, even the momentary belief in the instrumental useful of the process improvement initiative and the corresponding increase in *Resources to Improvement* is not enough to change the continued downward and increasingly negative *Perceived Rate of Change in Resources to Improvement*. And, with still positive *Perceived Rate of Change in Throughput* and the now negative *Perceived Rate of Change in Resources to*
Improvement, our manager again perceives a negative covariation between Throughput and process improvement. Again, she believes that work is more instrumentally useful than improvement (see Figure 20).

She continues to invest in work rather than improvement. Throughput rises as Resources go toward work and Yield continues to rise from previous investments (see Figure 15, 16 and 17). The process briefly goes through a “better” phase; Throughput surpasses the original level. But, the rise in Yield that is sustaining this “better” phase cannot last. As Resources to Improvement falls below initial levels (see Figure 22), Yield drops below original levels as well (see Figure 23). Throughput falls (see Figure 21). The process improvement fails.

6.7 The Postbifurcation Case
In the fourth case, the postbifurcation case (Push End 136 days), the process improvement initiative succeeds.

As in the prebifurcation case, our manager perceives a positive covariation between Throughput and Resources to Improvement. She changes her belief in the process improvement initiative. She invests in the Resources to Improvement. And, just as in prebifurcation case, days after investing in process improvement, she gets the information that the process does not work. This time, however, the covariation does not go negative long enough to have our manager learn the process improvement initiative does not work. She continues her investment in it. In time, her perception of the process improvement initiative improves, and she continues her investment in it. The process improvement initiative succeeds.
6.8 Push Until You See It Works

In the fifth case, Push End 200 Days, our manager continues the normative pressure until Day 200. Unlike the previous four situations, the Throughput rises not because of the end of the normative pressure frees up Resources for work. Instead, Throughput rises because the Throughput gains from Yield begin to offset the losses to Resources to Improvement. Still, until a sufficient positive covariation is learned on Day 270, our manager continues her instrumental allocation of Resources to Work. On Day 270, however, our manager then learns the process improvement initiative works. The process improvement initiative succeeds (see Figure 21, 22, and 23).

6.9 Pushing Forever

In the sixth and final case, our manager continues the normative pressure until day 500. At this point, she waits out the entire negative instrumental period. She learns the correct, positive covariation between Throughput and Resources to Improvement. The process improvement initiative succeeds (see Figure 21, 22, and 23).
Figure 15. Fraction of Optimal Throughput over 500 days

Figure 16. Fraction of Optimal Resources to Improvement over 500 days

Figure 17. Fraction of Optimal Yield over 500 days
Perceived Rate of Change in Throughput
(units/day)

0.15
0.12
0.09
0.06
0.03
0.00
-0.03
-0.06
-0.09
-0.12
-0.15

0 50 100 150 200 250 300 350 400 450 500

Time (days)

Figure 18. Perceived Rate of Change in Throughput over 500 days

Perceived Rate of Change in Resources to Improvement
(worker-hours/day)

0.15
0.12
0.09
0.06
0.03
0.00
-0.03
-0.06
-0.09
-0.12
-0.15

0 50 100 150 200 250 300 350 400 450 500

Time (days)

Figure 19. Perceived Rate of Change in Resources to Improvement over 500 days

Instrumental Pressure
(dimensionless)

3
2
1
0
-1
-2
-3

0 50 100 150 200 250 300 350 400 450 500

Time (days)

Figure 20. Instrumental Pressure over 500 days
Figure 21. Fraction of Optimal Throughput over 5000 days

Figure 22. Fraction of Optimal Resources to Improvement over 5000 days

Figure 23. Fraction of Optimal Yield over 5000 days
Figure 24. Perceived Rate of Change in Throughput over 5000 days

Figure 25. Perceived Rate of Change in Resources to Improvement over 5000 days

Figure 26. Instrumental Pressure over 5000 days
6.10 Normative Pressure Creates Three System States

The six cases describe six unique sets of dynamics that characterize the model as our manager is trying to improve the *Throughput* of her process. Figure 27 summarizes these results.

<table>
<thead>
<tr>
<th>Push End (days)</th>
<th>Outcome</th>
<th>Cause of “Better” Throughput</th>
<th>Perceives Positive Covariation</th>
<th>Learned Positive Covariation</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Failure</td>
<td>Normative Push Ends</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>50</td>
<td>Failure</td>
<td>Normative Push Ends</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>135</td>
<td>Failure</td>
<td>Normative Push Ends</td>
<td>Oscillates to No</td>
<td>Oscillates to No</td>
</tr>
<tr>
<td>136</td>
<td>Success</td>
<td>Normative Push Ends</td>
<td>Oscillates to Yes</td>
<td>Oscillates to Yes</td>
</tr>
<tr>
<td>200</td>
<td>Success</td>
<td>Yield increase</td>
<td>Oscillates to Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>500</td>
<td>Success</td>
<td>Yield increase</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Figure 27. Summary of six representative scenarios, varying *Push End* from 10 days to 500 days.

From Figure 27, we can define three key states of the model. First, if our manager does not invest in normative pressure long enough (Push End 10, 50, and 135), she will receive confounded feedback from the system. She will confound the drop in *Throughput* due to a decrease in *Resources to Work* with the increase in *Throughput* due to the increase in *Yield*. In the end, our manager will conclude that the process improvement technique as she has implemented it does not work. We will call this state Erroneous and Confounded Feedback. Second, if our manager sustains normative pressure long enough (Push End 136 and 200), she will receive momentary confusing feedback about the instrumental value of the process improvement technique. In time, however, with the momentum of
the investment in process capability, Yield will increase, and our manager will receive the correct feedback that the process improvement is instrumentally effective in increasing Throughput. We will call this state Confounded yet Correct Feedback. Third, if our manager sustains normative pressure still long (Push End 500), she will increase Yield, so the investment of Resources in process capability more than offset the decline in Throughput due to this investment. In this case, our manager will receive clear-cut feedback from the system that the process improvement initiative is instrumentally useful. We will call this state Clear Feedback.

Thus, with the three states that we have defined, we can conclude that, for process improvement initiatives to be successful, we must sustain normative pressure long enough to gain either correct or clear feedback from the system.

6.11 Boundedly Rational v. Perfect Process Information
In Section 5.1.9, we outlined the criteria for our manager having perfect process information. We found that she would quickly find the Optimal Yield and Optimal Throughput. In Section 5.2.1, we discussed why the knowledge and information processing capabilities required for having perfect process information were unreasonable and proposed that our manager was boundedly rational. In Figure 28 and 29, we show the Learned Improvement Productivity calculated using the boundedly rational and the perfect process information methods. At the start, the perfect process information starts positive and very high but drops quickly. In contrast, the boundedly rational curves (all Push End runs) start at much lower levels, the assumed equilibrium level (Work Productivity times Initial Yield), and go sharply negative. In all the boundedly rational cases, the process improvement technique does not initially appear to
work; it does not seem to be instrumentally effective. In the cases of failed implementations, the boundedly rational manager learns the process improvement does not work; the final Learned Improvement Productivity ends up negative. In the cases of successful implementations, however, the boundedly rational manager learns the process improvement initiative works; the final Learned Improvement Productivity ends up positive. And, furthermore, during the course of implementing the successful process improvement, the Learned Improvement Productivity goes sharply positive and declines to (nearly) meet the Learned Work Productivity.

From this contrast between manager with perfect process information and boundedly rational manager, we can see the dynamic implications of our assumptions about perception and learning. We can see our boundedly rational manager confounds a drop in Throughput due to the scarce resources (the Resource Constraint) with an increase in Throughput due to the improvements in process capability. Moreover, the drop comes immediately while the increase comes with a delay. This confounding leads our manager to learn – initially in some cases and conclusively in others – that the process improvement technique does not work. These results further emphasize that learning in dynamic systems is difficult and can lead one to strikingly wrong conclusions.
Figure 28. Learned Improvement Productivity over 500 days: Boundedly Rational v. Perfect Process Information

Figure 29. Learned Improvement Productivity over 5000 days: Boundedly Rational v. Perfect Process Information

- Push End 10 days
- Push End 50 days
- Push End 135 days
- Push End 136 days
- Push End 200 days
- Push End 500 days
- Initial
- Optimal
- Perfect Process Information
7. Initial Process Capability Affects Outcome

The initial process capability determines the outcome of the process improvement initiative. As we vary the Initial Resources to Improvement as a Fraction of Optimal Resources to Improvement for 0.1 to 1.0 by steps of 0.1, the Initial Yield varies logarithmically, because of the diminishing rate of returns (see left hand side of Figure 30). There are three distinct types of outcomes. When the Initial Resources to Improvement as a Fraction of Optimal Resources to Improvement is 0.95, the system does not change much. Yield stays nearly the same near the Optimal Yield (see Figure 30). Second, when the Initial Resources to Improvement as a Fraction of Optimal Resources to Improvement is in the range from 0.60 to 0.90, the process capability decays; Yield drops (see Figure 30). When the initial condition is in this higher range (from 0.60 to 0.90), the confounding of decline in Throughput due to decrease in Resources to Work and the increase in Throughput due to the delayed increase in Yield is more severe. Even though in these runs the Push Time is 1000, our manager still fails to learn the process improvement technique works. She decreases her allocation of Resources to Resources to Improvement. Third, when the Initial Resources to Improvement as a Fraction of Optimal Resources to Improvement is in the range from 0.10 to 0.50, the process capability improves. The process improvement initiative works; Yield increases (see Figure 30). This success is the converse of the previous, second case. That is, when the process capability is poor (Yield is lower), the decline in Resources to Work has a relatively lower impact on Throughput. And, similarly, because of the diminishing returns to improvement, when the process is poor, an increase in Resources to Improvement has a relatively greater impact on Throughput. Together, these two
trends cause the effect of confounding to be diminished; our manager sees the instrumental effect of increasing Resources to Improvement more clearly.

Thus, within the scope of our model, we can conclude that it should be easier to implement process improvement techniques in systems with lower initial process capability systems than those with higher initial process capability because the lower ones will give our manager more clear-cut, less confounded feedback.
Figure 30. Effect of Initial Yield on outcome over 5000 days. Lower Initial Yield results in higher final Yield. Higher Initial Yield results in lower final Yield. Very high Initial Yield (0.95) stays near Optimal Yield. Runs labeled with Initial Resources to Improvement values.
8. Conclusion

In conclusion, we have developed the beginning of an integrated, interdisciplinary theory of process improvement implementation. We have developed new system dynamics structures for process capability, perception, and learning. We have shown that scarce resources and the new process capability and throughput structures give rise to *Optimal Throughput* and *Optimal Yield*. Our manager then tries to improve the process – increase *Yield* – while maintaining or improving the process *Throughput*. That is, she tries to move toward the *Optimal Throughput* and *Optimal Yield* simultaneously. We have shown that the scarcity of *Resources* coupled with the desired to meet these two goals gives rise to less than optimal dynamics of perception and learning about the effectiveness of the process improvement initiative. We found that a reasonable yet bounded rational manager will confound an increase in *Throughput* due to the investment in the process improvement with a decrease in *Throughput* due to the scarcity of *Resources*. This confounding condition leads to initially and, perhaps, permanently wrong perceptions and beliefs about the instrumental effectiveness of the process improvement. It also gives rise to three new states – *Erroneous and Confounded Feedback*, *Confounded yet Correct Feedback*, and *Clear Feedback* – that characterize the system. And, finally, we show how systems with initially lower capability produce more clear-cut information about the instrumental effectiveness of the process improvement techniques and, therefore, have more successful implementations.
9. Future Work

So far, we have demonstrated the effects of Push Time and the initial process capability (Initial Resources to Improvement and Initial Yield) on the outcome of the model. We can further use our model to test the effects of the “worse before better” dynamics and Throughput pressure or Backlog pressure on the instrumental feedback loops. These tests would further clarify our manager’s double bind – that is, how can she simultaneously improve the process and increase Throughput.

We can also add structure to the model to capture our manager’s situation more realistically and to develop our integrated, interdisciplinary model further. We could do the following:

1. Expected Improvement Delay. So far, our manager does not account for the improvement delay when forming her perception of the productivity of the improvement process. We could delay the information from Resources to Improvement to allow her to better correlate her investment in the improvement process with the payoff of that investment.

2. Risk. Process improvement is a risky venture; we could add a Risk discounting factor to account for our manager’s risk aversion.

3. Ambiguity. Like Risk, we should account for our manager Ambiguity aversion.

4. Salience. Our manager is biased toward processes that have more Salience. Throughput is more salient than improvement, so our manager should be biased toward Working Harder and increasing Resources to Work. Salience in an extreme form represents the Fundamental Attribution Error. See Repenning and Sterman (2000) for more details.

5. Learning Time Constant. We have not assumed it takes time to learn how to do the new process improvement technique.

6. Cycle Time and WIP. Especially in product development, these factors may influence the outcome of the model.
# Appendix 1. Variable List

<table>
<thead>
<tr>
<th>Variable by Sector</th>
<th>Low</th>
<th>High</th>
<th>Realistic</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Goals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goal RI fraction of Optimal RI</td>
<td>0.00</td>
<td>2.00</td>
<td>0.50</td>
<td>Schneiderman</td>
</tr>
<tr>
<td>Push End</td>
<td>50</td>
<td>1200</td>
<td>135</td>
<td>From program of the month to a more sustained program</td>
</tr>
<tr>
<td>Normative Time Constant</td>
<td>100</td>
<td>500</td>
<td>360</td>
<td>Repenning</td>
</tr>
<tr>
<td><strong>Initial Conditions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial RI as fraction of Optimal RI</td>
<td>0.00</td>
<td>1.00</td>
<td>0.20</td>
<td>Full range; realistic is set on very low end</td>
</tr>
<tr>
<td><strong>Process Throughput Sector</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work Productivity</td>
<td>*</td>
<td>*</td>
<td>1</td>
<td>Arbitrary: just scales throughput</td>
</tr>
<tr>
<td><strong>Process Capability Sector</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time Constant Due to Entropy</td>
<td>500</td>
<td>5000</td>
<td>3600</td>
<td>From employee turnover rate (1.5 to 10 years), new equipment and processes (4 to 15 y)</td>
</tr>
<tr>
<td>Improvement Time</td>
<td>50</td>
<td>1000</td>
<td>100 to low: Schneiderman's manufacturing; 800 high: Schneiderman's product development</td>
<td></td>
</tr>
<tr>
<td>Improvement Productivity</td>
<td>0.001</td>
<td>0.100</td>
<td>0.010</td>
<td>Scale to Schneiderman's data</td>
</tr>
<tr>
<td>Maximum Number of Problems</td>
<td>*</td>
<td>*</td>
<td>100</td>
<td>Arbitrary</td>
</tr>
<tr>
<td>Maximum Yield</td>
<td>0.90</td>
<td>1.00</td>
<td>1.00</td>
<td>Physically realistic ranges</td>
</tr>
<tr>
<td>Minimum Yield</td>
<td>0.00</td>
<td>0.90</td>
<td>0.50</td>
<td>Physically realistic ranges</td>
</tr>
<tr>
<td><strong>Resource Allocation Sector</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>0.0010</td>
<td>0.2000</td>
<td>0.0200</td>
<td>Makes the system work</td>
</tr>
<tr>
<td>Throughput Pressure at No Throughput Gap</td>
<td>0.0001</td>
<td>0.1000</td>
<td>0.0250</td>
<td>Pressure from the Throughput Gap when the Gap is zero</td>
</tr>
<tr>
<td><strong>Perception Sector</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recent Time Constant</td>
<td>10</td>
<td>100</td>
<td>30</td>
<td>Low: manufacturing can process data quickly and accurately; High: product development has to judge informally</td>
</tr>
<tr>
<td>Historical Time Constant</td>
<td>10</td>
<td>360</td>
<td>30</td>
<td>Guess, if too long then system does not act as derivative getting the rate of change</td>
</tr>
<tr>
<td>T Threshold Fraction</td>
<td>1.00E-06</td>
<td>1.00E-04</td>
<td>1.00E-05</td>
<td>Low: 10-6 is .036% over 360 days; High: 10-4 is 3.6% over 360 days</td>
</tr>
<tr>
<td>RI threshold fraction</td>
<td>1.00E-06</td>
<td>1.00E-04</td>
<td>1.00E-05</td>
<td>Low: 10-6 is .036% over 360 days; High: 10-4 is 3.6% over 360 days</td>
</tr>
<tr>
<td>Learning Sector</td>
<td>0</td>
<td>1000</td>
<td>100 Guess</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>----</td>
<td>------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>RI factor</td>
<td>0</td>
<td>1000</td>
<td>100 Guess</td>
<td></td>
</tr>
<tr>
<td>T factor</td>
<td>0</td>
<td>1000</td>
<td>100 Guess</td>
<td></td>
</tr>
<tr>
<td>Relative Change in T Update Fraction</td>
<td>0.020</td>
<td>0.002</td>
<td>0.010 Reciprocal of Time Constant to Throughput Productivities</td>
<td></td>
</tr>
<tr>
<td>Relative Change in RI Update Fraction</td>
<td>0.020</td>
<td>0.002</td>
<td>0.010 Reciprocal of Time Constant to Throughput Productivities</td>
<td></td>
</tr>
<tr>
<td>Effect of Information in Difference RI on Update Fraction</td>
<td>0.1</td>
<td>10.0</td>
<td>1.0 Guess</td>
<td></td>
</tr>
<tr>
<td>Minimum Time to Change Covariation</td>
<td>10</td>
<td>180</td>
<td>30 Guess</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 2. Bibliography


Appendix 3. Model in Vensim Equation Format

After Push Resources=

\[ \text{worker*hours/day} \]

range=

\[ 0.02 \]

\[ \text{DMNL} \]

backlog= INTEG (orders, initial backlog)

\[ \text{units} \]

Backlog Pressure Switch=

\[ 1 \]

\[ \text{DMNL} \]

backlog time=

\[ 10 \]

\[ \text{days} \]

Below T and RI Update Fraction=

\[ 1 \]

\[ 1/\text{day} \]

Change in Desired Resources to Improvement=

Normative Change in Desired Resources to Improvement + Instrumental Change in Desired Resources to Improvement

\[ \text{worker*hours/day/day} \]

Change in Desired Resources to Work=

Instrumental Change in DRW

\[ \text{hours*worker/day/day} \]

Change in Historical RI=

(Recent RI-Historical RI)/T Historical RI

\[ \text{worker*hours/(day*day)} \]

Change in Historical T=

(Recent T-Historical T)/T Historical T

\[ \text{units/day/day} \]

Change in Improvement Productivity=
IF THEN ELSE( T Threshold Check, IF THEN ELSE(RI Threshold Check, Change in IPT from Covariation)
 ,Change in IPT from Relative Change in Throughput
 ),IF THEN ELSE(RI Threshold Check,Change in IPT from Relative Change in RI,Change in IPT from below thRI and below thT
 )
 = units/(worker*hour*day)

change in IPT flow used=
  IF THEN ELSE( T Threshold Check, IF THEN ELSE(RI Threshold Check,1,3), IF THEN ELSE(\n RI Threshold Check,2,4))
  = DMNL
  = units/(worker*hour*day)

Change in IPT from below thRI and below thT=
  (IPIPT from below thRI and below thT-Learned Improvement Productivity)*Below T and RI
  Update Fraction
  = units/(worker*hour*day)
  = units/(worker*hour*day)

Change in IPT from Covariation=
  (IPIPT from Covariation-Learned Improvement Productivity)*Update Fraction for Covariation
  = units/(worker*hour*day)
  = units/(worker*hour*day)

Change in IPT from Relative Change in RI=
  (IPIPT from Relative Change in RI-Learned Improvement Productivity)*Relative Change in RI
  Update Fraction
  = units/(worker*hour*day)
  = units/(worker*hour*day)

Change in IPT from Relative Change in Throughput=
  (IPIPT from Relative Change in T-Learned Improvement Productivity)*Relative Change in T
  Update Fraction
  = units/(worker*hour*day)
  = units/(worker*hour*day)

change in PT=
  (Throughput-Perceived Throughput)/time to change perceived throughput
  = units/(day*day)
  = units/(day*day)

Change in Recent RI=
  (Resources to Improvement-Recent RI)/T Recent RI
  = hours*worker/(day*day)
  = hours*worker/(day*day)

Change in Recent T=
  (Throughput-Recent T)/T Recent T
  = units/day/day
  = units/day/day

Change in Recent Y=
  (Yield-Recent Y)/T Recent Y
  = DMNL/day
  = DMNL/day
Defect Rate=
\[(1 - \text{Yield}) \times \text{Gross Throughput} \]
\[\sim \text{units/day}\]

Desired Resources to Improvement = \text{INTEG (}
\text{Change in Desired Resources to Improvement,}
\text{Initial Resources to Improve)}
\[\sim \text{hours*worker/day}\]

Desired Resources to Work = \text{INTEG (}
\text{Change in Desired Resources to Work,}
\text{Initial Resource to Do Work)}
\[\sim \text{worker*hours/day}\]

Desired Throughput =
\[\text{Initial Throughput} \times \text{Fraction of Initial} \]
\[\sim \text{units/day}\]

Diagnosed Problems = \text{INTEG (}
\text{Rate of Diagnosing Problems} - \text{Rate of Completing Experiments,}
\text{Initial Problems per Stock)}
\[\sim \text{problems}\]

Difference RI =
\[\text{Recent RI} - \text{Historical RI} \]
\[\sim \text{worker*hours/day}\]

Difference T =
\[\text{Recent T} - \text{Historical T} \]
\[\sim \text{units/day}\]

Effect of Backlog on Throughput Pressure:
\[[(0,0)-(1,100)],(0,1),(1,10)]\]
\[\sim \text{DMNL}\]

Effect of Information in Difference RI on Update Fraction =
\[1 \sim \text{day/(worker*hour)}\]
\[\sim 1 \text{ uses } \tau_{\text{cv}} = 100 \text{ for } t < 1000 \quad 0.1 \text{ uses } \text{ErRI for most all times except briefly early on. Now using } 0.5\]

Effect of T Gap on Pressure:
\[[(0,0)-(1,10)],(-1,0),(-0.492355,0.307018),(-0.259939,0.394737),(-0.0948012,0.657895),\]
\[0.153),(0.29052,4.95614),(0.480122,7.10526),(0.657492,8.5649),(0.82263,9.64912)\]
Entropy Into Undiscovered Problems =
(Maximum Number of Problems - Total Problems) / Time Constant Due to Entropy

fR Diagnose =
W Diagnose / Total IR

fR Experiment =
W Experiment / Total IR

fR Implement =
W Implement / Total IR

Fraction of Initial =
0.9

Fraction of Optimal Resources to Improvement =
Resources to Improvement / Optimal Resources to Improve

Fraction of Optimal Throughput =
Throughput / Optimal Throughput

Fraction of Optimal Yield =
Yield / Optimal Yield

Fraction of Problems to Max Number =
Total Problems / Maximum Number of Problems

Fractional Throughput Gap =
Throughput Gap / Goal Throughput

fri =
Desired Resources to Improvement / Total Desired Resources
frW = Desired Resources to Work/Total Desired Resources

Goal RI fraction of Optimal RI =
1

Goal Throughput = Initial Throughput
units/day

Gross Throughput = Work Productivity * Resources to Work
units/day

Historical RI = INTEG (Change in Historical RI, Initial Resources to Improve)
worker * hours / day

Historical T = INTEG (Change in Historical T, Initial Throughput)
units / day

historical time constant = 30 days

homo forrester v homo economus switch =
1
Hey, that's forrester not foster. Homo Forrester = 1 and Homo Economus = 0

Hours per day =
10 hours / day

Improvement Productivity =
0.01 problem / (worker * hour)
Improvement Time = 100 ~ day

Indicated Update Fraction for Covariation =
1/Minimum Time to Change Covariation
~ 1/day

Initial backlog =
0 ~ units

Initial Gross Process Throughput =
Initial Resource to Do Work * Work Productivity
~ units/day

Initial Perceived Improvement Productivity for Throughput =
Initial Yield * Work Productivity
~ units/(worker*hour)

Initial Problems per Stock =
Initial Total Problems / Stock Order
~ problems

Initial Resource to Do Work =
Resources - Initial Resources to Improve
~ worker*hours/day

Initial Resources to Improve =
Optimal Resources to Improve * Initial RI as fraction of Optimal RI
~ worker*hours/day

Initial RI as fraction of Optimal RI =
0.2
~ DMNL
~ was 0.5 now 0.2

Initial Throughput =
Initial Gross Process Throughput * Initial Yield
~ units/day

Initial Total Problems =
Maximum Number of Problems / (1 + ((Improvement Productivity * Time Constant Due to Entropy * Initial Resources to Improve) / (Maximum Number of Problems * Stock Order * Stock Order)))
Initial Yield =
\[
\frac{((\text{Minimum Yield} - \text{Maximum Yield}) \times (\text{Initial Total Problems}/\text{Maximum Number of Problems})) + \text{Maximum Yield}}{\text{DMNL}}
\]

Instantaneous Partial Derivative of Throughput wrt RI =
\[
\frac{(\text{Resources to Work} \times \text{Work Productivity} \times (\text{Maximum Yield} - \text{Minimum Yield}) \times \text{Improvement Productivity}}{\text{Time Constant Due to Entropy})/((\text{Stock Order} + ((\text{Improvement Productivity} \times \text{Time Constant Due to Entropy})/\text{Maximum Number of Problems} \times \text{Stock Order}))^2 \times \text{Maximum Number of Problems}}\]
\[
\frac{\text{units/(worker*hour)}}{\text{DMNL}}
\]

Instrumental Change in Desired Resources to Improvement =
\[
\text{Instrumental Switch} \times (\text{Max}(\text{Min(Pressure on Improvement, range), -range}) \times \text{Desired Resources to Improvement}}/\text{Instrumental Time Constant}
\]
\[
\frac{\text{worker*hours/(day*day)}}{\text{DMNL}}
\]

Instrumental Change in DRW =
\[
\text{Instrumental Switch} \times (\text{Max}(\text{Min(Pressure on Work, range), -range}) \times \text{Resources to Work}/\text{Instrumental Time Constant}
\]
\[
\frac{\text{hours*worker/day/day}}{\text{DMNL}}
\]

Instrumental Pressure =
\[
(\text{Learned Work Productivity} - \text{IF THEN ELSE(homo forrester v homo economus switch, Learned Improvement Productivity}}/\text{Instantaneous Partial Derivative of Throughput wrt RI)/\text{Work Productivity}
\]
\[
\frac{\text{DMNL}}{\text{DMNL}}
\]

Instrumental Switch =
\[
1
\]
\[
\frac{\text{DMNL}}{\text{DMNL}}
\]

Instrumental Time Constant =
\[
50
\]
\[
\frac{\text{day}}{\text{day}}
\]

IPIPT from below thRI and below thT =
\[
\text{Learned Improvement Productivity}
\]
\[
\frac{\text{units/(worker*hour)}}{\text{DMNL}}
\]
IPIPT from Covariation=
    Perceived Improvement Productivity
    ~ units/(worker*hour)
    ~

IPIPT from Relative Change in RI=
    Relative Change in RI*Learned Improvement Productivity
    ~ units/(worker*hour)
    ~

IPIPT from Relative Change in T=
    Relative Change in Throughput*Learned Improvement Productivity
    ~ units/(worker*hour)
    ~

Learned Improvement Productivity= INTEG (Change in Improvement Productivity, Initial Perceived Improvement Productivity for Throughput)
    ~ units/(worker*hour)
    ~

Learned Work Productivity=
    Work Productivity*Recent Y
    ~ units/(worker*hour)
    ~

Maximum Number of Problems=
    100
    ~ problems
    ~ the theoretical maximum number of problems if the process were to degrade completely
    ~

Maximum Yield=
    1
    ~ DMNL
    ~

Minimum Time to Change Covariation=
    100
    ~ day
    ~ now using 30
    ~

Minimum Yield=
    0.5
    ~ DMNL
    ~

Normative Change in Desired Resources to Improvement=
    Max((Resources to Improve Goal - Resources to Improvement)/NormativeTime Constant , 0)
    ~ worker*hours/(day*day)
    ~

NormativeTime Constant=
Optimal Gross Process Throughput =
Optimal Resource to Do Work * Work Productivity
~ units/day

Optimal Resource to Do Work =
Resources - Optimal Resources to Improve
~ worker*hours/day

Optimal Resources to Improve =
- Stock Order * ((Maximum Yield * Maximum Number of Problems * Stock Order) - (sqrt((Maximum Yield * Maximum Number of Problems) * (Maximum Yield - Minimum Yield) * (Maximum Number of Problems) * Stock Order + Resources * Time Constant Due to Entropy * Improvement Productivity)) / (Maximum Yield * Improvement Productivity * Time Constant Due to Entropy))
~ worker*hours/day

Optimal Throughput =
Optimal Gross Process Throughput * Optimal Yield
~ units/day

Optimal Total Problems =
Maximum Number of Problems / (1 + ((Improvement Productivity * Time Constant Due to Entropy * Optimal Resources to Improve) / (Maximum Number of Problems * Stock Order * Stock Order problems)

Optimal Yield =
((Minimum Yield - Maximum Yield) * (Optimal Total Problems / Maximum Number of Problems)) + Maximum Yield
~ DMNL

orders =
Desired Throughput - Throughput
~ units/day

P Diagnose =
Improvement Productivity
~ problem / (worker * hour)

P Experiment =
Improvement Productivity
Problem/(worker\*hour)

P Implement=
  Improvement Productivity
  Problem/(worker\*hour)

Perceived Improvement Productivity=
  ZIDZ(Perceived Rate of Change in Throughput, Perceived Rate of Change in Resources to Improvement)
  units/(worker\*hour)

Perceived Rate of Change in Resources to Improvement =
  IF THEN ELSE(ABS(RI Rate)<RI Threshold, 0, RI Rate)
  worker\*hours/(day\*day)

Perceived Rate of Change in Throughput =
  IF THEN ELSE(ABS(T rate)<Throughput Threshold, 0, T rate)
  units/day/day

Perceived Throughput = INTEG (change in PT, Initial Throughput)
  units/day

Pressure on Improvement =
  -Instrumental Pressure*Throughput Pressure
  DMNL

Pressure on Work =
  Throughput Pressure*Instrumental Pressure
  DMNL

Push End =
  1000
  days

Push Start =
  0
  days

R Diagnose =
  fR Diagnose*Resources to Improvement
  worker\*hours/day
R Experiment=
   fR Experiment*Resources to Improvement
   \sim worker*hours/day
   \sim |

R Implement=
   fR Implement*Resources to Improvement
   \sim worker*hours/day
   \sim |

Rate of Completing Experiments=
   Min(Diagnosed Problems/T Experiment,( (Diagnosed Problems/Maximum Number of Problems\)
       )\*R Experiment\*P Experiment))
   \sim problems/day
   \sim |

Rate of Diagnosing Problems=
   Min(Rate of Diagnosing Problems Resources Limited,Rate of Diagnosing Problems Stock Limited)
   \sim problems/day
   \sim |

Rate of Diagnosing Problems Resources Limited=
   (Undiscovered Problems/Maximum Number of Problems)*R Diagnose\*P Diagnose
   \sim problems/day
   \sim |

Rate of Diagnosing Problems Stock Limited=
   Undiscovered Problems/T Diagnose
   \sim problems/day
   \sim |

Rate of Implementing Solutions=
   Min(Solved Problems/T Implement, ((Solved Problems/Maximum Number of Problems)*P
   Implement\)
   \sim *R Implement))
   \sim problems/day
   \sim |

ratio initial to optimal throughput=
   Initial Throughput/Optimal Throughput
   \sim DMNL
   \sim |

Recent RI= INTEG ( Change in Recent RI,
   Initial Resources to Improve)
   \sim hours*worker/day
   \sim |

Recent T= INTEG ( Change in Recent T,
   Initial Throughput)
   \sim units/day
   \sim |
recent time constant =
  30
  ~ days

Recent Y = INTEG (Change in Recent Y, Initial Yield)
  ~ DMNL

Relative Change in RI =
  ZIDZ(Recent RI, (Recent RI + RI Rate * RI factor * (Learned Improvement Productivity / ABS(Learned Improvement Productivity)))
  ~ DMNL

Relative Change in RI Update Fraction =
  Update Fraction for Covariation
  ~ 1/day
  ~ 1 over day-1

Relative Change in T Update Fraction =
  0.01
  ~ 1/day
  ~ should this be the same as 1/Time to Change Improvement Productivity OR
    SHOULD THIS BE 0.01 DMNL

Relative Change in Throughput =
  (T factor * T rate * (Learned Improvement Productivity / ABS(Learned Improvement Productivity)) + Recent T) / Recent T
  ~ DMNL

Resources =
  Hours per day * Total Effective Workforce
  ~ hours * worker / day
  ~ resources available to do work or improve process

Resources to Improve Goal =
  IF THEN ELSE((Time < Push Start), Initial Resources to Improve, IF THEN ELSE((Time >= Push Start)
    AND (Time < Push End), Resources to Improvement Goal
    , After Push Resources))
  ~ hours * worker / day

Resources to Improvement =
  Resources * frl
  ~ worker * hours / day
Resources to Improvement Goal =
  \text{Goal RI fraction of Optimal RI} \times \text{Optimal Resources to Improve}
  \sim \quad \text{worker} \times \text{hours/day}
  \sim \quad \text{ }$

Resources to Work =
  \text{frW} \times \text{Resources}
  \sim \quad \text{worker} \times \text{hours/day}
  \sim \quad \text{ }$

RI factor =
  100
  \sim \quad \text{day}
  \sim \quad 1
  \text{ }$

RI Rate =
  \text{Difference RI/T Historical RI}
  \sim \quad \text{worker} \times \text{hours/(day\times day)}
  \sim \quad \text{ }$

RI Threshold Check =
  \text{IF THEN ELSE} (\text{ABS(RI Rate)} < \text{RI Threshold}, 0, 1)
  \sim \quad \text{DMNL}
  \sim \quad \text{ }$

RI threshold fraction =
  1 \times 10^{-5}
  \sim \quad 1/\text{day}
  \sim \quad \text{ }$

RIThreshold =
  \text{Recent RI} \times \text{RI threshold fraction}
  \sim \quad \text{worker} \times \text{hours/(day\times day)}
  \sim \quad \text{ }$

Solved Problems = \text{INTEG (}
  \text{Rate of Completing Experiments - Rate of Implementing Solutions},
  \text{Initial Problems per Stock)}
  \sim \quad \text{problems}
  \sim \quad \text{ }$

Stock Order =
  3
  \sim \quad \text{DMNL}
  \sim \quad \text{ }$

T Diagnose =
  \text{Improvement Time}
  \sim \quad \text{day}
  \sim \quad \text{ }$

T Experiment =
  \text{Improvement Time}
  \sim \quad \text{day}  

T factor=
  100
  ~ day
  ~

T Historical RI=
historical time constant
  ~ day
  ~

T Historical T=
historical time constant
  ~ day
  ~

T Implement=
  Improvement Time
  ~ day
  ~

T rate=
  Difference T/T Historical T
  ~ units/(day*day)
  ~

T Recent RI=
recent time constant
  ~ day
  ~

T Recent T=
recent time constant
  ~ day
  ~

T Recent Y=
recent time constant
  ~ day
  ~

T Threshold Check=
  IF THEN ELSE(ABS(T rate)<Throughput Threshold, 0, 1)
  ~ DMNL
  ~

T Threshold Fraction=
  1e-005
  ~ 1/day
  ~

Throughput=
  Gross Throughput*Yield
  ~ units/day
  ~
Throughput Gap =
  Goal Throughput - Perceived Throughput
  ~ units/day
  ~

Throughput Goal Switch =
  0
  ~ DMNL
  ~

Throughput Pressure at No Throughput Gap =
  0.025
  ~ DMNL
  ~ 0.025

Throughput Pressure with No Backlog =
  0.025
  ~ DMNL
  ~

Throughput Threshold =
  Recent T*T Threshold Fraction
  ~ units/day/day
  ~

Time Constant Due to Entropy =
  3600
  ~ days
  ~ the time constant for the rate at which people leave, the process is forgotten, or machines break down

  time to change perceived throughput =
  30
  ~ day
  ~ this could be the same the recent time constant

Total Desired Resources =
  Desired Resources to Improvement + Desired Resources to Work
  ~ worker*hours/day
  ~

Total Effective Workforce =
  100
  ~ workers
  ~ number of employees

Total IR =
  W Diagnose + W Experiment + W Implement
  ~ worker*hours
  ~
Total Problems =
Diagnosed Problems + Solved Problems + Undiscovered Problems

Undiscovered Problems = INTEG (Entropy Into Undiscovered Problems - Rate of Diagnosing Problems,
Initial Problems per Stock)

Update Fraction based on Information in Difference RI =
Effect of Information in Difference RI on Update Fraction * ABS(Perceived Rate of Change in Resources to Improvement)

Update Fraction for Covariation =
Min(Indicated Update Fraction for Covariation, Update Fraction based on Information in Difference RI)

W Diagnose =
Undiscovered Problems / P Diagnose

W Experiment =
Diagnosed Problems / P Experiment

W Implement =
Solved Problems / P Implement

Work Productivity =
1 / units/(worker*hour)

Yield =
((Minimum Yield - Maximum Yield) * Fraction of Problems to Max Number) + Maximum Yield

~ DMNL