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

by

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Bachelor of Science in Chemistry
Stanford University, 1989

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of
Master of Science

at the

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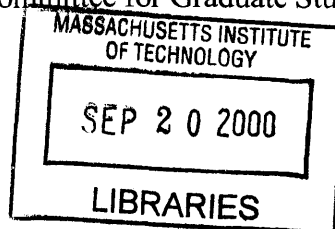
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ABSTRACT

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.

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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.

Physical

Resources

Resources to Work

Resources to Work

Resources to Improvement

Resources to Improvement

Process Throughput

Yield

Process Capability

Throughput

Perception

Yield

Behavioral

Perceived Productivities

Learning

Learned Productivities

Resource Allocation
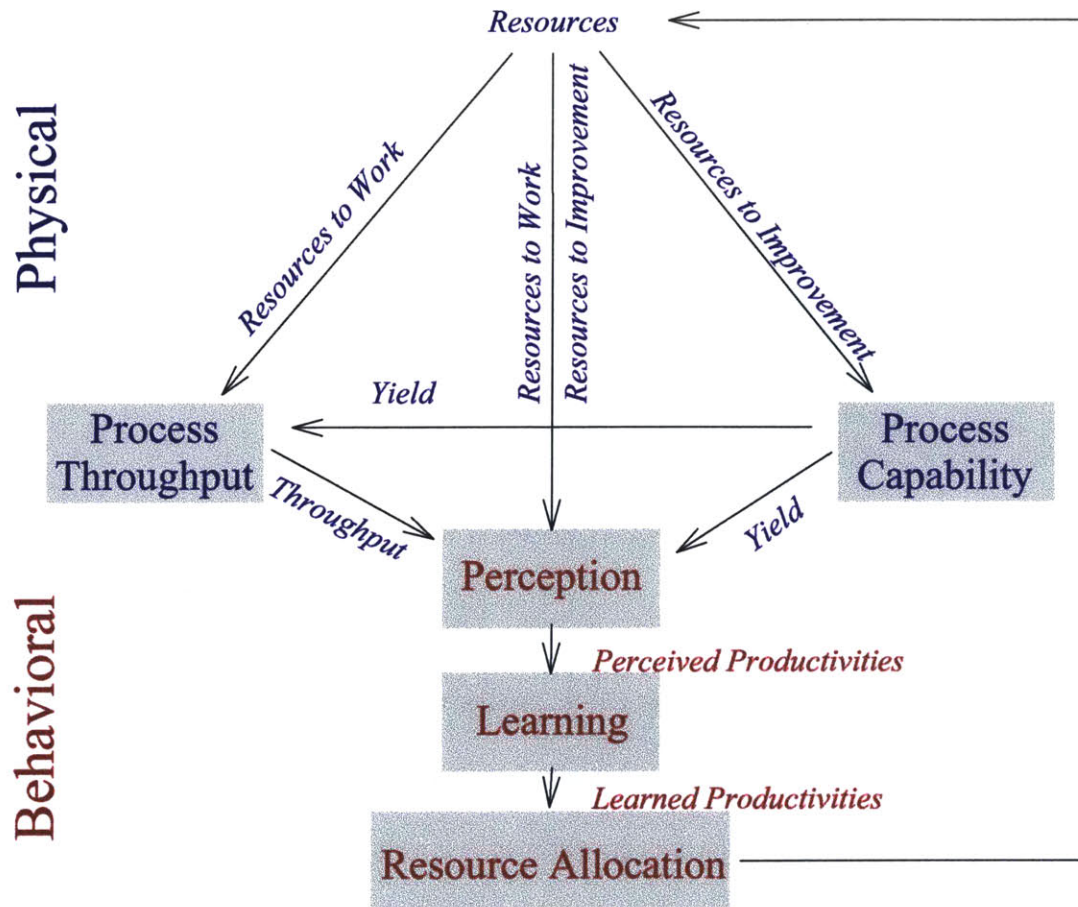
Figure 1. Gray boxes indicate the five sectors in the model. Italic type indicates information or materials flowing between these sectors.

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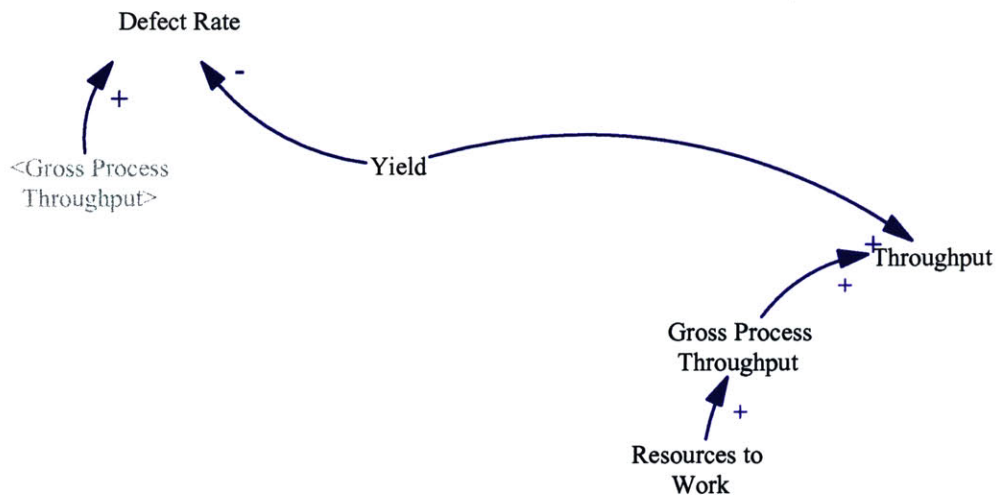
Figure 2. The relationship among *Gross Process Throughput*, *Throughput*, and *Defect Rate* expressed in the form of a causal loop diagram (Forrester 1961, Richardson and Pugh 1981, Richardson 1991, Weick 1979). Adapted from Repenning and Sterman (2000).

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. $Y = -(Y_{max} - Y_{min})\dfrac{P_{Total}}{M} + Y_{max}$

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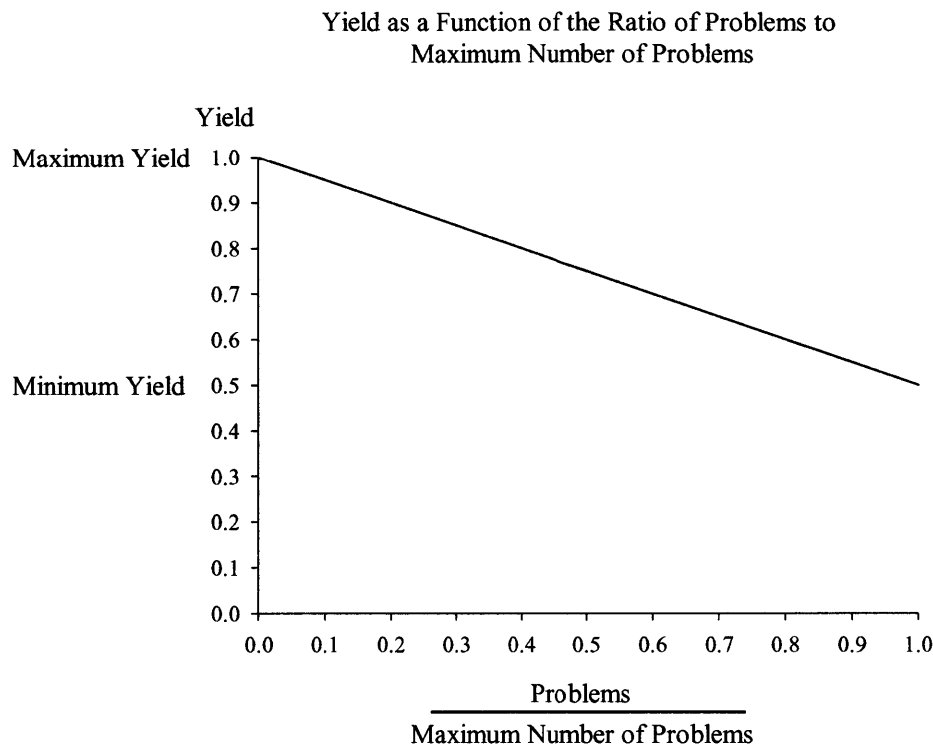
Figure 3. *Yield* **as a linear function of the ratio of** *Problems* **to** *Maximum Number of Problems.*

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:

$$\text{Eq 6.} \quad PIR = \frac{(M-P)}{\tau_E}$$

Where M is *Maximum Number of Problems* as before, and τ_E is the *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:

Eq. 7 $$\frac{dP}{dt} = -\frac{P}{\tau_I}$$

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 τ_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 $$\frac{dP}{dt} = -\left(\frac{P}{M}\right) R_I \pi_{I_{Total}}$$

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 τ_I; instead, we now have *Total Improvement Productivity* $\pi_{I_{Total}}$ – 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:

Stock Number (n)	Stock	Stock Limited Outflow Rate
1	Undiscovered Problems	Diagnose Problems
2	Diagnosed Problems	Solve Problems
3	Solved Problems	Implement Solutions

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:

Eq. 9 $$\frac{dP_n}{dt} = -\frac{P_n}{\tau_{I_n}}$$

where P_n is one of the three substocks, and τ_{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*, π_{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:

$$\text{Eq. 10} \quad W_n = \frac{P_n}{\pi_{I_n}}$$

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 US/(US+THEM)

allocation rule (Kalish and Lillien 1986) to divide *Resources to Improvement* among the

three outflows:

$$\text{Eq. 11} \quad R_{I_n} = R_I \frac{W_n}{\sum_n W_i}$$

We revise Eq. 8 to be:

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

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:

$$\text{Eq. 13} \quad \frac{dP}{dt} = \min\left(-\left(\frac{P_n}{M}\right) R_{I_n} \pi_{I_n}, -\frac{P_n}{\tau_{I_n}}\right)$$
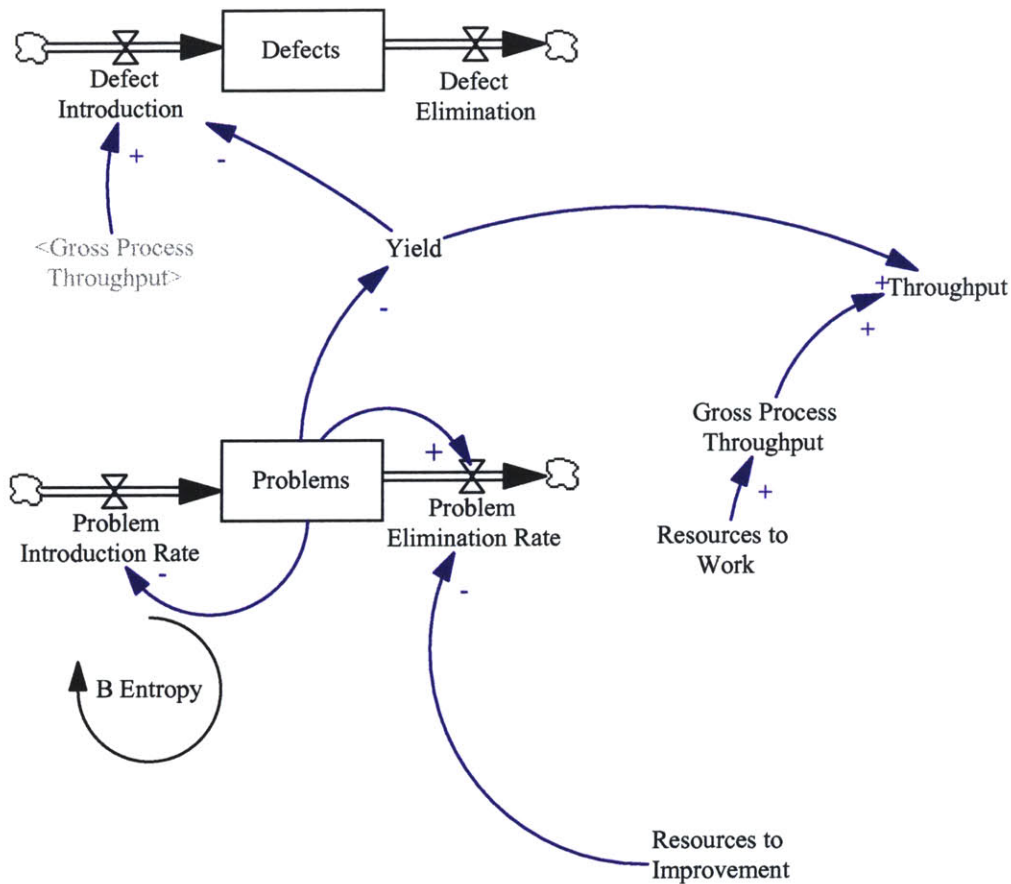
Figure 4. ***Problems*** **and** ***Defects*** **as stocks (level or state variable) denoted by rectangle (Forrester 1961). A stock is the integration (accumulation) of its inflows less its outflows, denoted by the straight arrows with valves. Adapted from Repenning and Sterman (2000).**

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:

Eq. 14 $R = R_w + R_I$

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*:

Eq. 15 $P_{Total} = \dfrac{zM}{\left(z + \dfrac{\pi_I \tau_E R_I}{zM} \right)}$

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*:

$$\text{Eq. 16} \quad T = (R - R_I)\pi_W \left[\frac{-z(Y_{Max} - Y_{Min})}{\left((z + \frac{\pi_I \tau_E R_I}{zM}) \right)} + Y_{max} \right]$$

Setting the derivative of Eq. 16 equal to zero and solving for R_I, we get the *Optimal*

Resources to Improvement:

$$\text{Eq. 17} \quad R_I^* = -\frac{z\left(zMY_{Max} - \sqrt{MY_{max}(Y_{max} - Y_{min})(z^2 M + R\tau_E \pi_I)}\right)}{Y_{Max}\tau_E \pi_I}$$

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

the *Optimal Yield* and *Optimal Throughput*, respectively

$$\text{Eq. 18} \quad Y^* = \left(\frac{-z(Y_{max} - Y_{min})}{z - \frac{MY_{Max} - \sqrt{MY_{max}(Y_{max} - Y_{min})(z^2 M + R\tau_E \pi_I)}}{MY_{Max}}} - Y_{Max} \right)$$

$$\text{Eq. 19} \quad T^* = \pi_W (R - R_I^*) Y^*$$

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

Resources to Work
(worker-hours/day)

Iso-Throughput
(units/day)

Resource Constraint (1000 worker-hours/day)

1000 ■ Initial
● Optimal
800
600
400
200
0

800
600
400
200

0   200   400   600   800   1000

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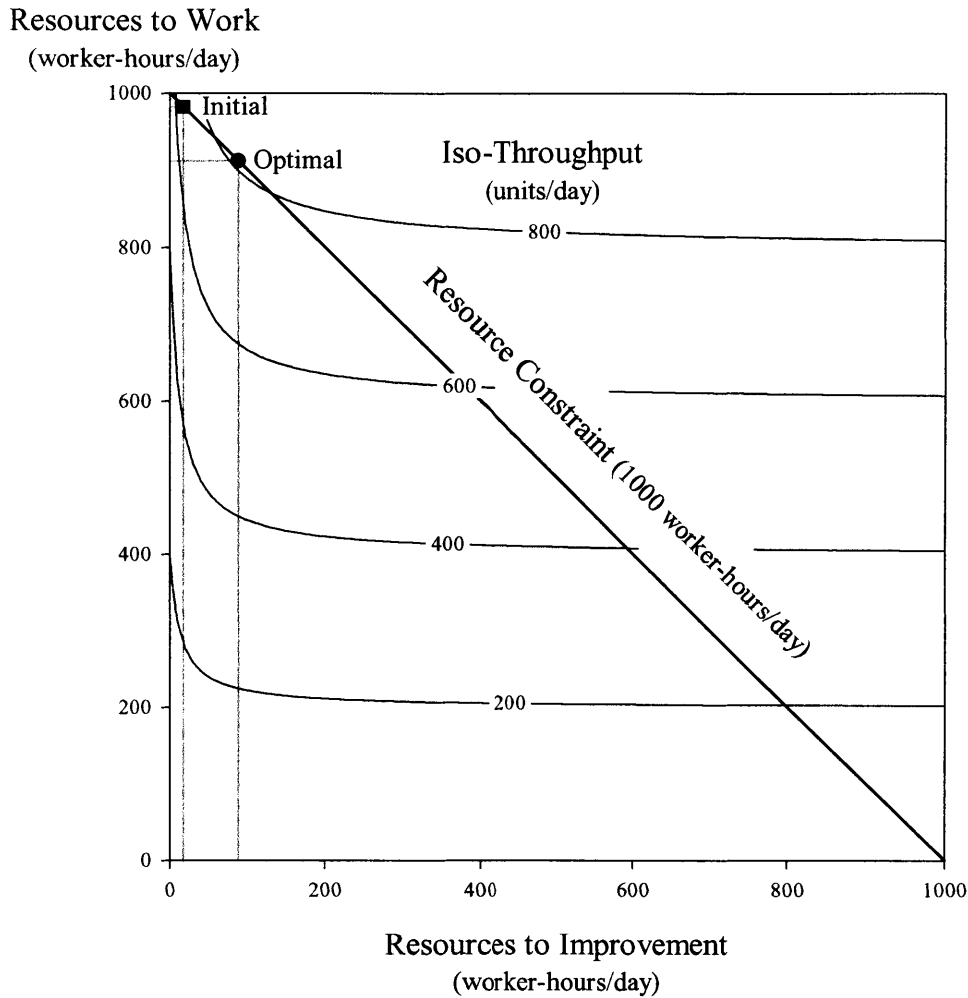
Figure 5. The intersection of the Resource Constraint Curve and the Iso-Throughput lines gives the *Initial* and *Optimal Resources to Improvement*, *Initial* *Optimal Resources to Work*, and *Initial* and *Optimal Throughput*.

Throughput Based on Resources to Improvement

Throughput
(units/day)

(Resources Constrained to 1000 worker-hours/day)

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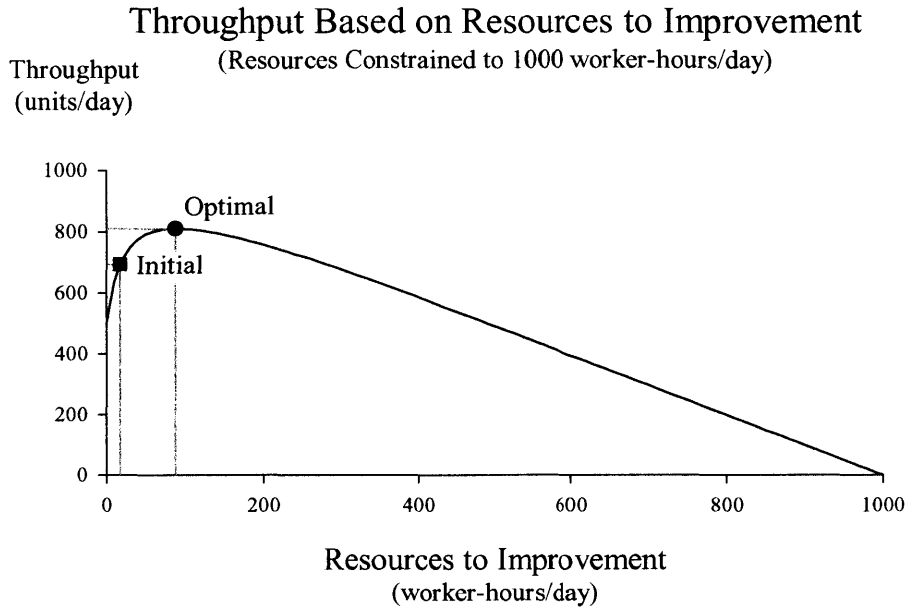
Figure 6. The Resource-Throughput Hill. For a given *Resources* (1000 worker-hours/day), the *Throughput* curve is shown. *Initial* and *Optimal Throughput* are shown. Note the steep gradient from *Initial Throughput* to *Optimal Throughput* as *Resources to Improvement* is increased.

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:

$$\text{Eq. 20} \quad \frac{dDR_{I_{Norm}}}{dt} = Max\left(\frac{GR_I - R_I}{\tau_{Norm}}, 0 \right)$$

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

35

the manager desires, she will not use normative pressure to cut back their improvement

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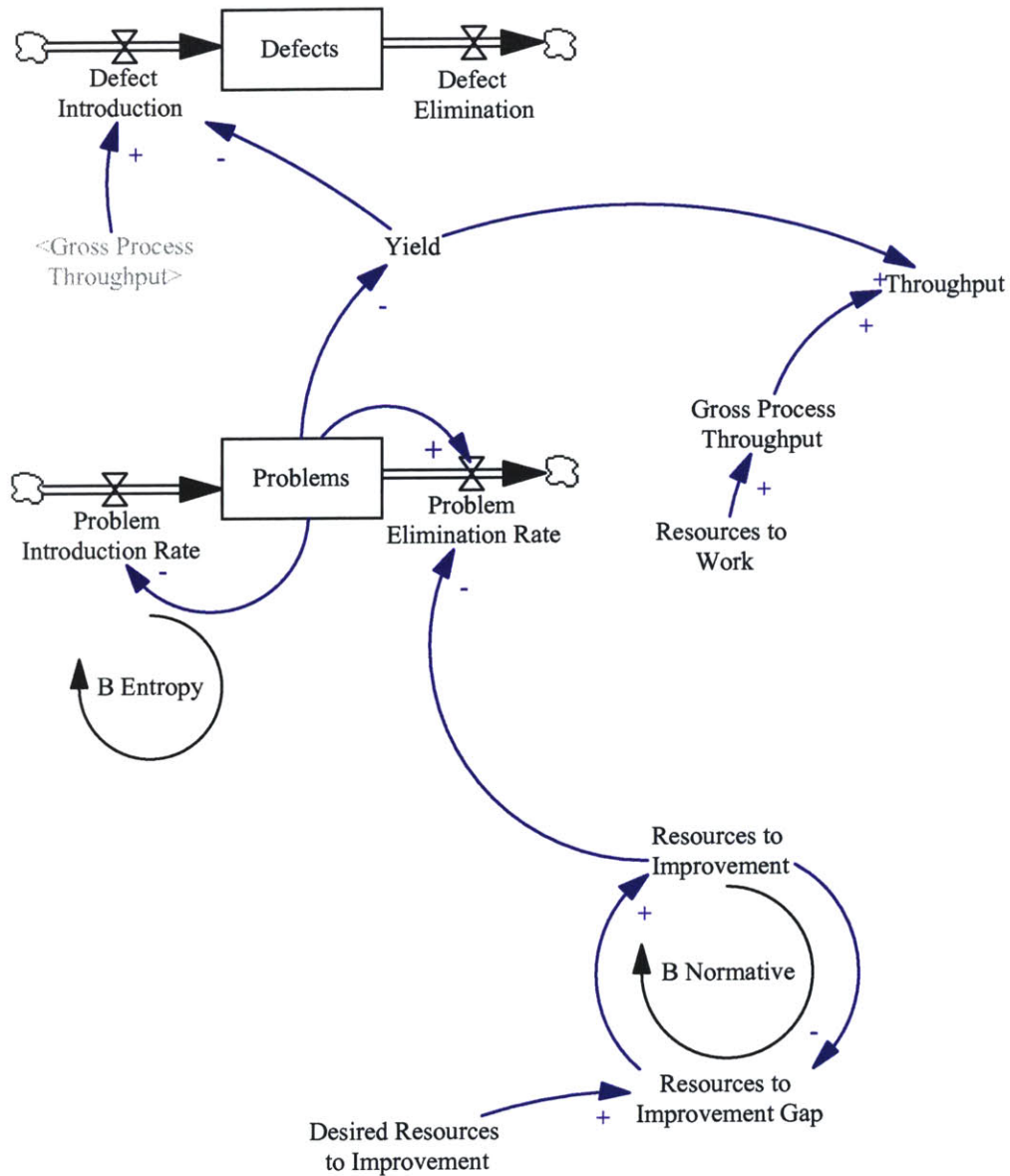
Figure 7. Manager tries to improve the process by setting the *Desired Resources to Improvement*, calculating the difference between the desired and actual, and trying to close this gap. Adapted from Repenning and Sterman (2000).

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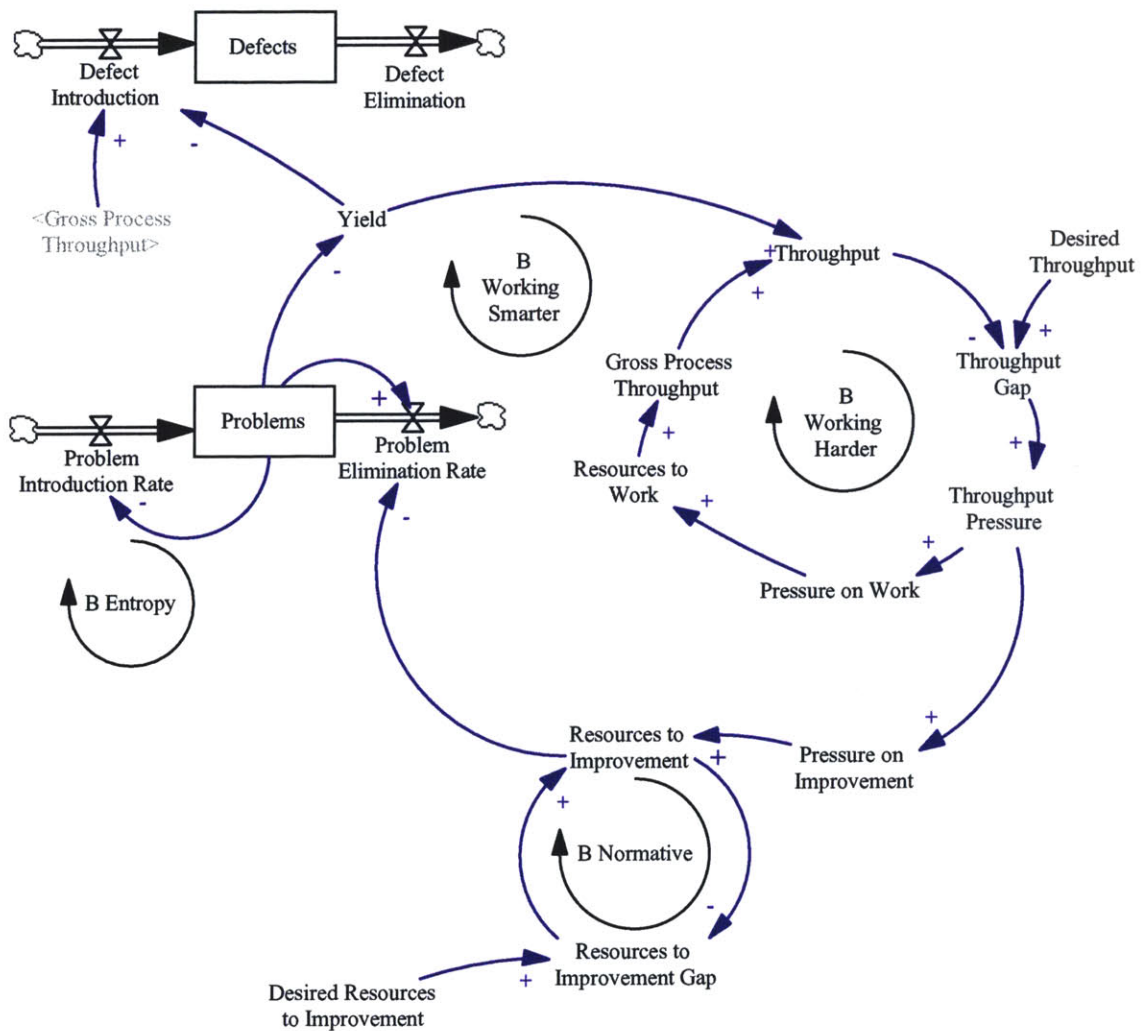
Figure 8. Our Manager can close the *Throughput Gap* either by increasing *Resources to Improvement*, increasing the *Yield*, and increasing *Throughput* or by increasing *Resources to Work* and increasing *Throughput*. Adapted from Repenning and Sterman (2000).

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).
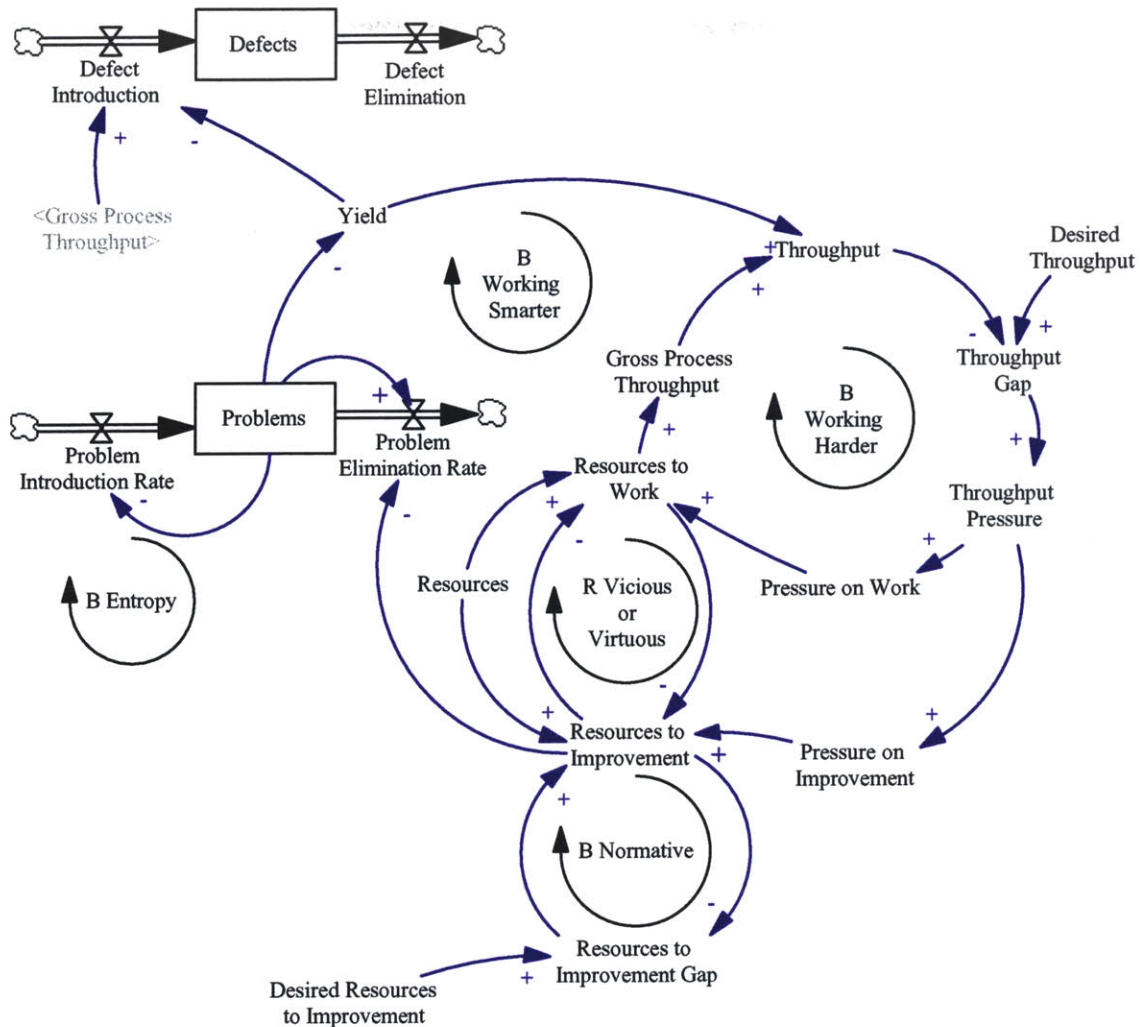
Figure 9. The Vicious and Virtuous reinforcing feedback created by finite and scarce resources. Adapted from Repenning and Sterman (2000).

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_0) to get the *Throughput Pressure* (TP)

(see Figure 9). This relationship is expressed in Eq. 21 as follows:

Eq. 21 *TP = TP$_0$ EffectTG(TG)*

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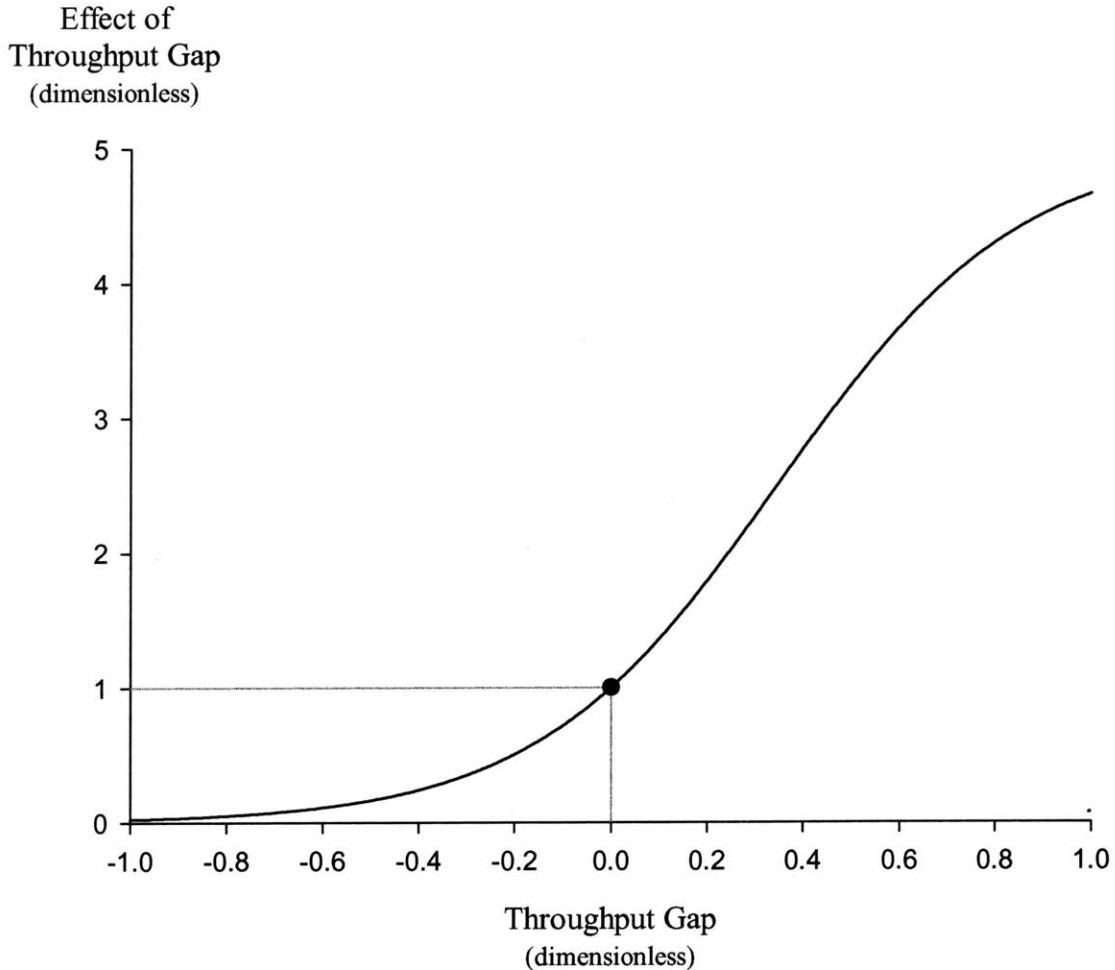
Figure 10. Logistic Function of *Effect of Throughput Gap on Throughput Pressure*. When *Throughput* equals *Throughput Goal*, *Throughput Gap* is zero, and the *Effect of Throughput Gap* is 1.0.

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.

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*.

Eq. 23 $$P_W = IP \cdot TP$$

Eq. 24 $$P_I = IP \cdot TP$$

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

Eq. 24 $$\frac{dDR_{I_{Inst}}}{dt} = \frac{DR_I Max(Min(P_I, range), -range)}{\tau_{Inst}}$$

Eq. 25 $$\frac{dDR_{W_{Inst}}}{dt} = \frac{DR_W Max(Min(P_W, range), -range)}{\tau_{Inst}}$$

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 productivities 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
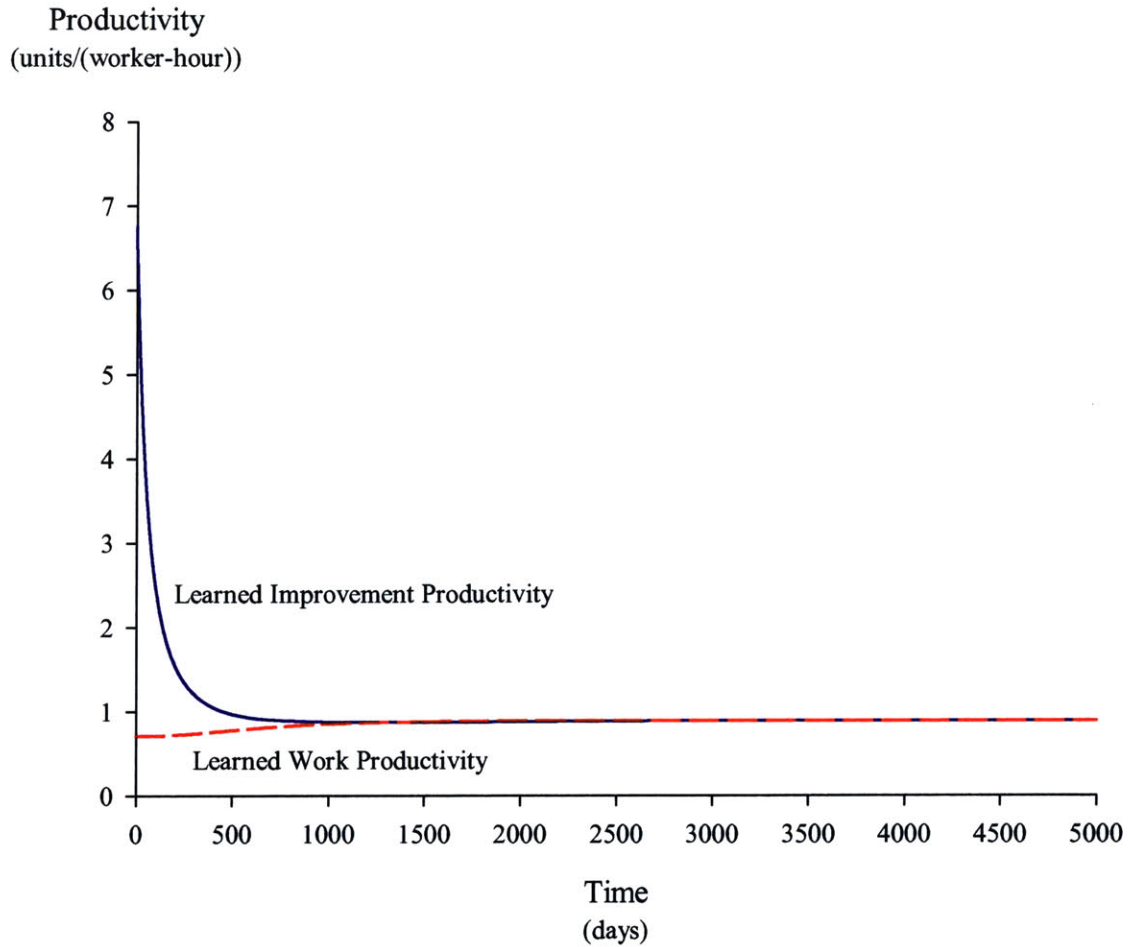
Figure 11. Perfect Process Information: Learned Improvement Productivity vs. Learned Work Productivity. Note that Learned Improvement Productivity starts at 6.75 units/(worker-hour), much higher than Learned Improvement Productivity, which starts at 0.71 units/(worker-hour). The process improvement initiative is seen as highly productive.

Perfect Process Information:
Fraction of Optimal Throughput
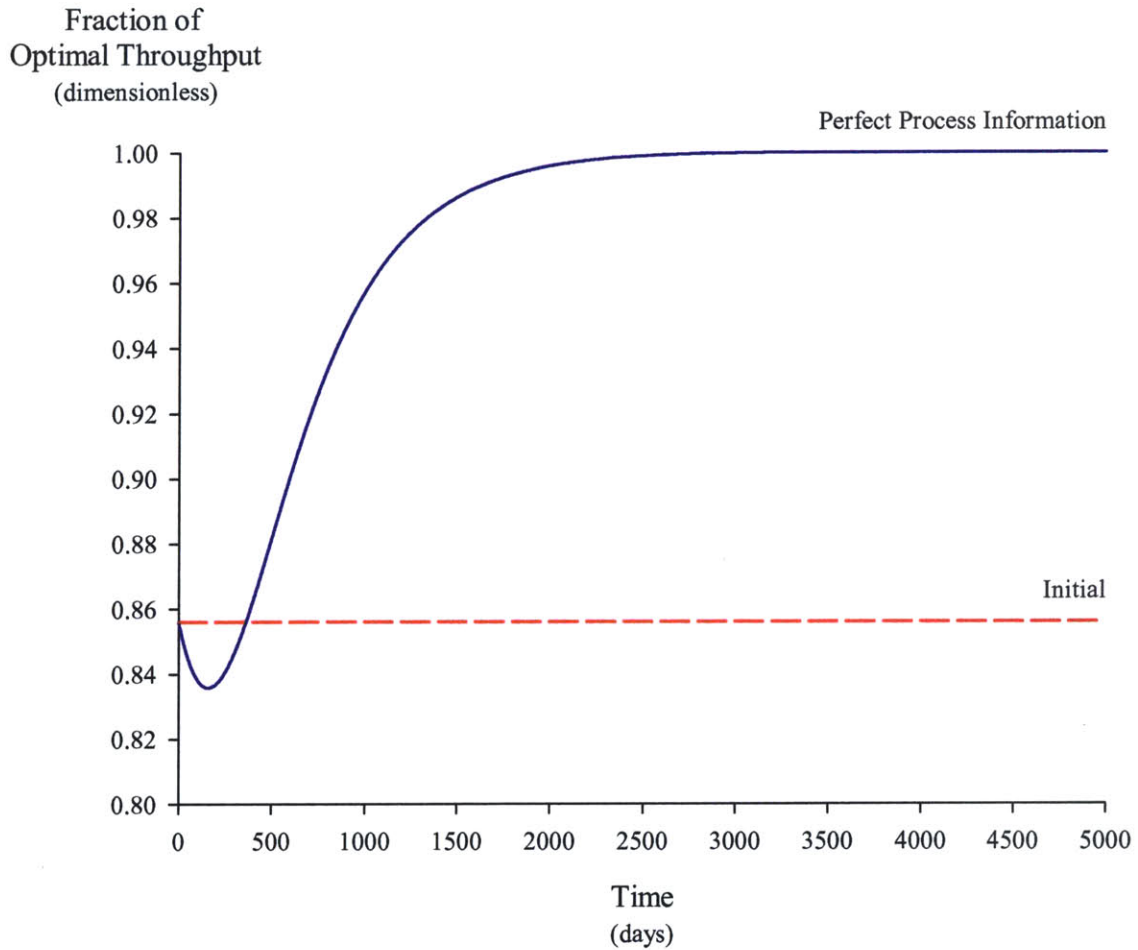
Figure 12. Perfect Process Information vs. Initial for Fraction of Optimal Throughput. For Perfect Process Information, the Fraction of Optimal Yield dips down and then rises to the optimal level. This dip is the "worse before better" mentioned in the literature.

Fraction of
Optimal Yield
(dimensionless)
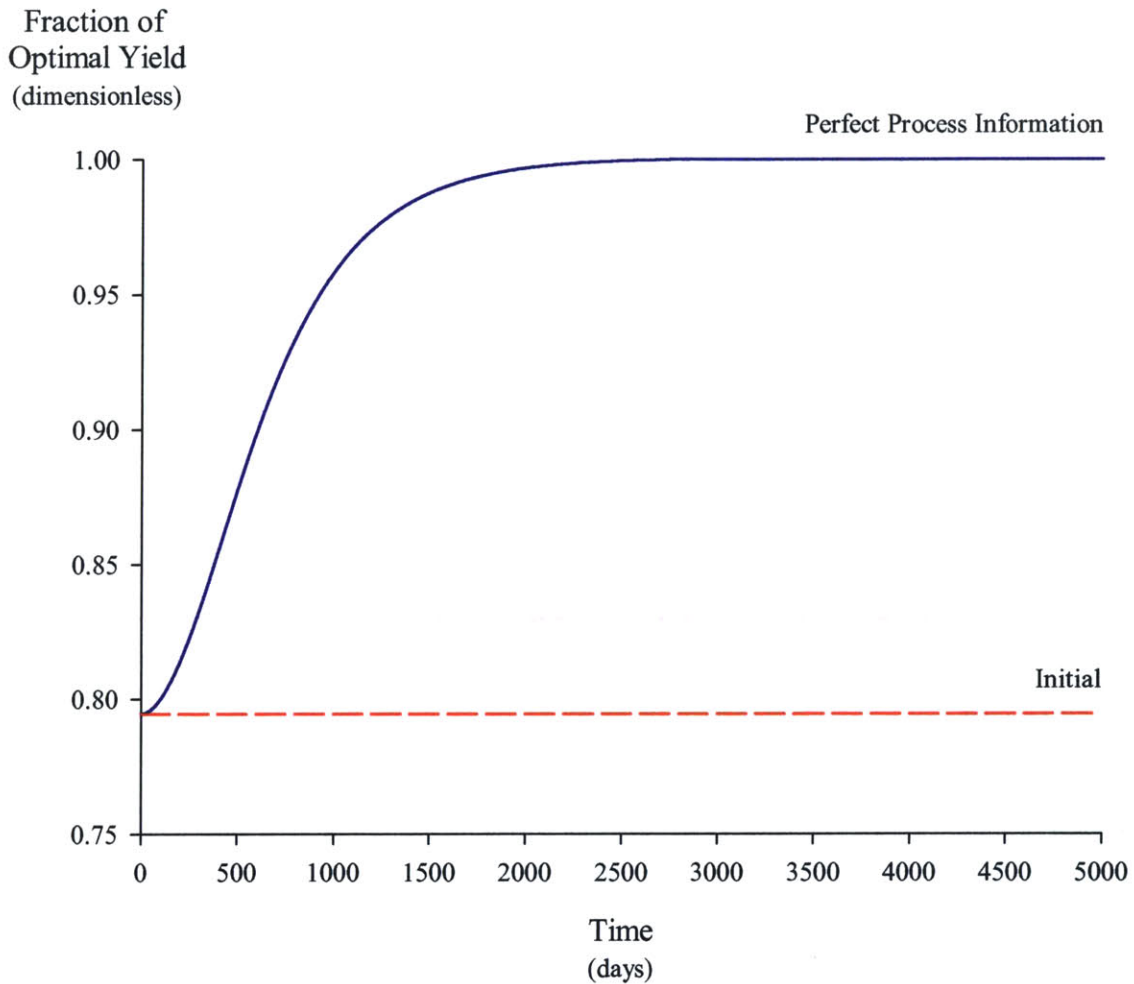
Figure 13. Perfect Process Information v. Initial for Fraction of Optimal Yield. Note, for the Perfect Process Information, the Fraction of Optimal Yield is initially flat because of the third-order delay in the Process Capability sector. Later, the Fraction of Optimal Yield rises to 1.0 – the optimal 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 smoothes 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:

Eq. 28 $\Delta I = kI$

where ΔI 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:

Eq. 29 $thT = thfT \cdot T_{Recent}$

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*:

Eq. 30 $P\Delta T = \Delta T$ if $\Delta T \geq thT$

$P\Delta T = 0$ if $\Delta T < 0$

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:

Eq. 31 $P\pi_W = \pi_W Y_{\text{Re}cent}$

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*:

Eq. 32 $P\pi_I = \dfrac{P\Delta T}{P\Delta R_I}$

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).

	$P\Delta R_I$	
	$<thRI$	$>thRI$

$P\Delta T$

$P\Delta T$	$<thRI$	$>thRI$
$<thT$	0	$\left(\left[\left[\left(\dfrac{R_{I_{Recent}}}{R_{I_{Recent}}+\Delta R_I f_{R_I}}\right)L\pi_I\,sign(L\pi_I)\right]-L\pi_I\right]u_{cov}\right)$
$>thT$	$\left(\left[\left[\left(\dfrac{T_{Recent}+\Delta Tf_T}{T_{Recent}}\right)L\pi_I\,sign(L\pi_I)\right]-L\pi_I\right]u_T\right)$	$\left(P\pi_I - L\pi_I\right)u_{cov}$

Eq. 33 Learning adjustments used based on variables values relative to their thresholds

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 ΔR_I times E,

the *Effect of Information in Difference Resources to Improvement on Update Fraction*, to

get:

Eq. 34 $u_{cov} = \max(E\Delta R_I, u_{cov_0})$

That is, as the amount of change in *Resources to Improvement* increases the u_{cov} increases up to a maximum u_{cov_0}. The other quadrant has a fixed update fraction.
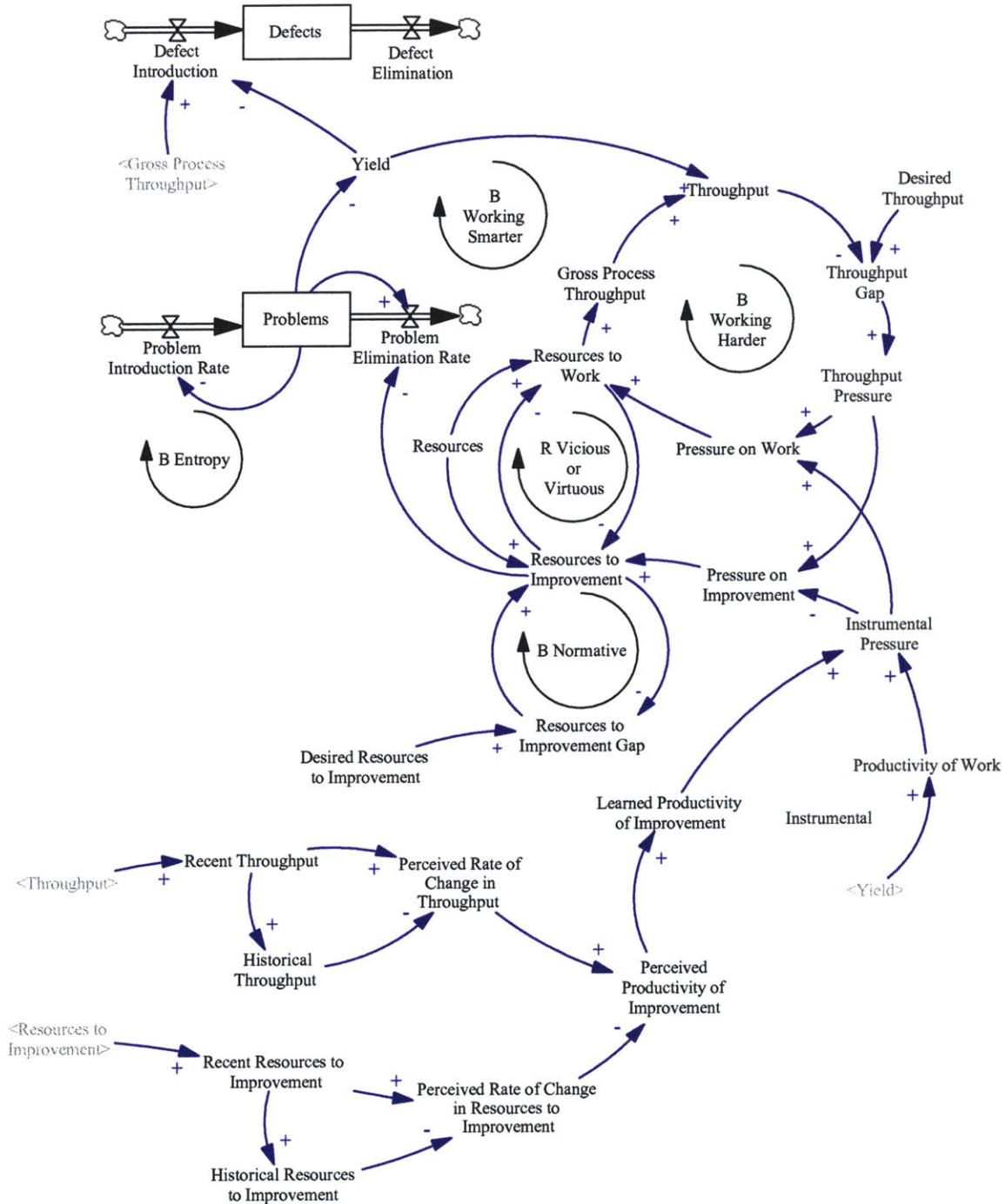
Figure 14. Our manager perceives, learns, and acts on the productivity of work and improvement to close the *Throughput Gap*.

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).

Throughput: Fraction of Optimal
(dimensionless)

Perception Delay
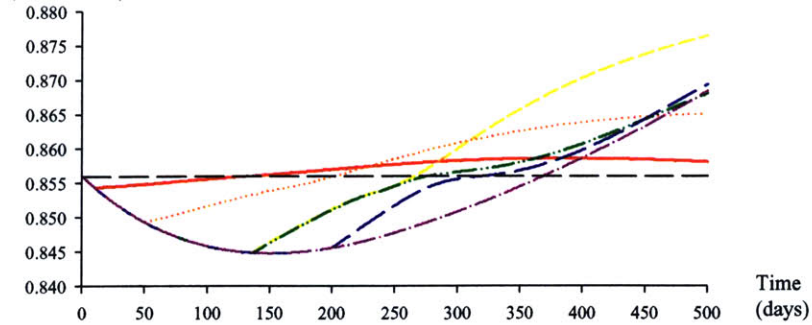
Figure 15. Fraction of Optimal Throughput over 500 days

Resources to Improvement: Fraction of Optimal
(worker-hours/day)

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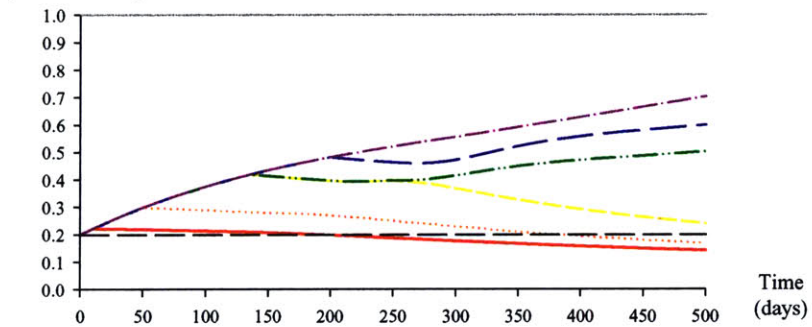
Figure 16. Fraction of Optimal Resources to Improvement over 500 days

Improvement Delays

Implementation Delay

Yield: Fraction of Optimal
(dimensionless)

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
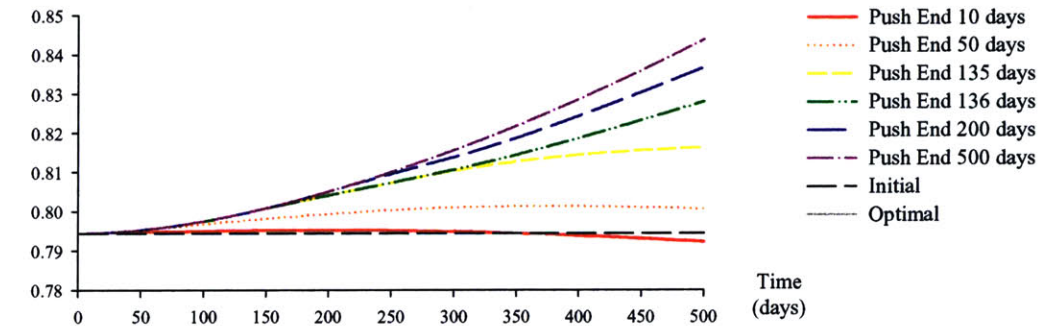
Figure 17. Fraction of Optimal Yield over 500 days

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Perceived Rate of Change in Throughput
(units/day²)
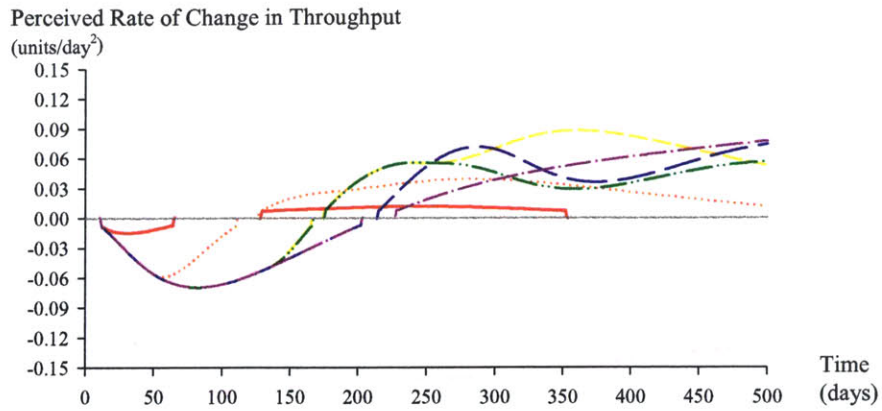
Figure 18. Perceived Rate of Change in Throughput over 500 days

Perceived Rate of Change in Resources to Improvement
(worker-hours/day²)
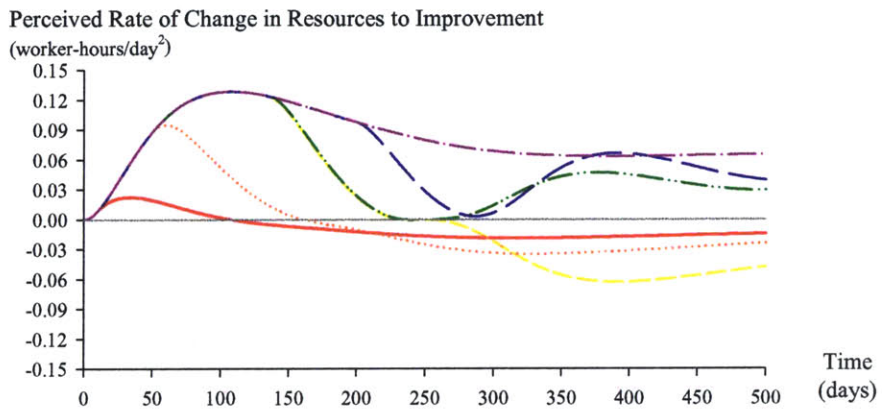
Figure 19. Perceived Rate of Change in Resources to Improvement over 500 days

Learning
Delay

Instrumental Pressure
(dimensionless)
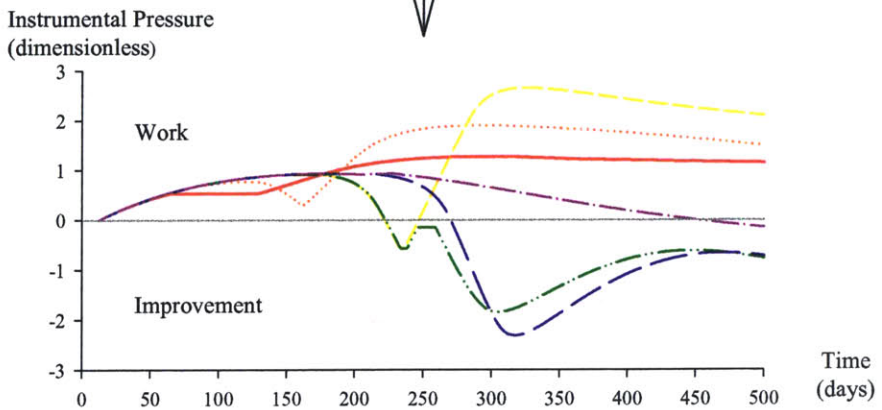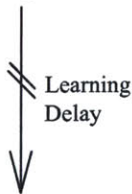
Work

Improvement

Figure 20. Instrumental Pressure over 500 days

Throughput: Fraction of Optimal
(dimensionless)
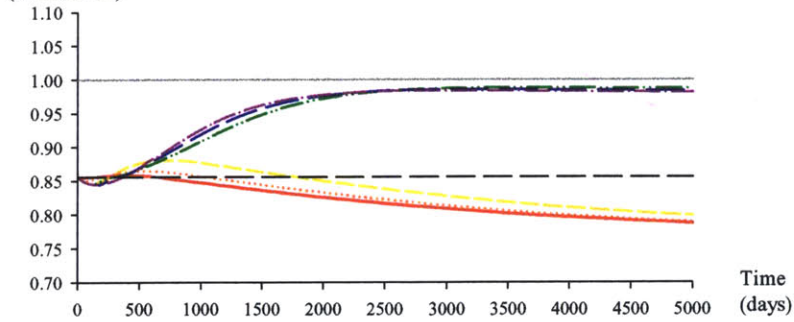
Figure 21. Fraction of Optimal Throughput over 5000 days

Perception Delay

Resources to Improvement: Fraction of Optimal
(worker-hours/day)
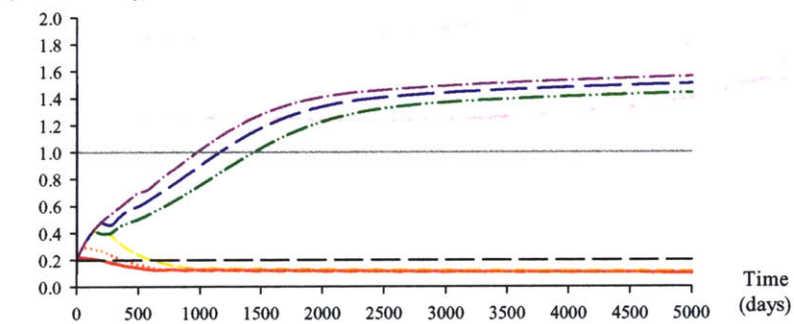
Figure 22. Fraction of Optimal Resources to Improvement over 5000 days

Perception Delay

Implementation
Delay

Improvement
Delays

Yield: Fraction of Optimal
(dimensionless)

——— Push Time 10 days
········· Push Time 50 days
– – – Push Time 135 days
–··– Push Time 136 days
——— Push Time 200 days
–·–· Push Time 500 days
– – Initial
——— Optimal
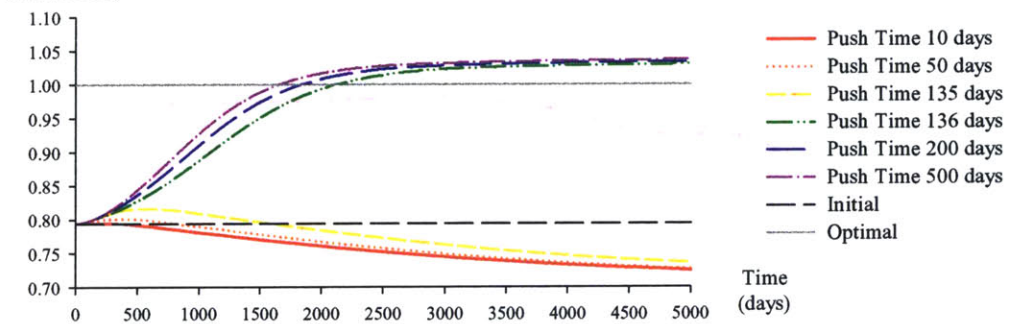
Figure 23. Fraction of Optimal Yield over 5000 days

Perceived Rate of Change in Throughput
(units/day²)
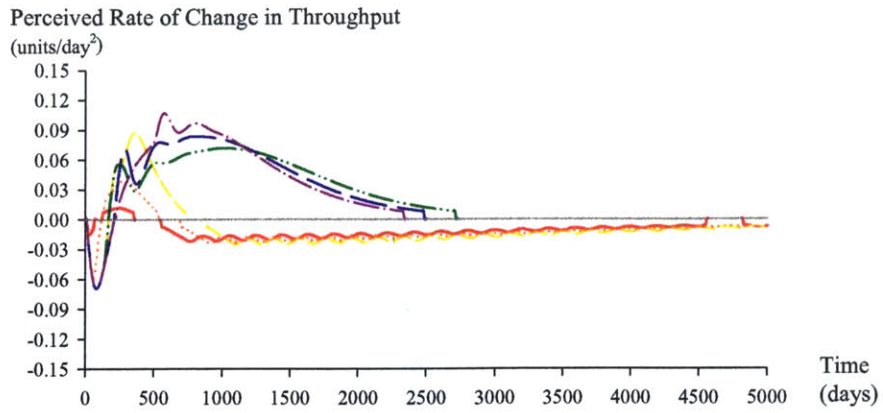
Figure 24. Perceived Rate of Change in Throughput over 5000 days

Perceived Rate of Change in Resources to Improvement
(worker-hours/day²)
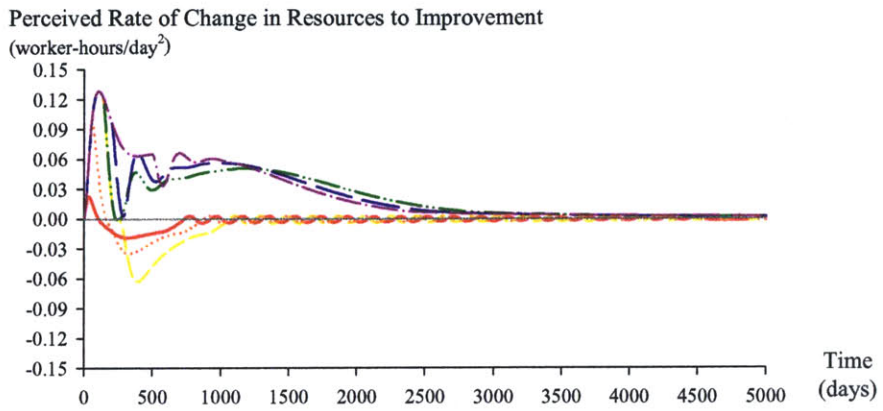
Figure 25. Perceived Rate of Change in Resources to Improvement over 5000 days

Learning
Delay

Instrumental Pressure
(dimensionless)

Work
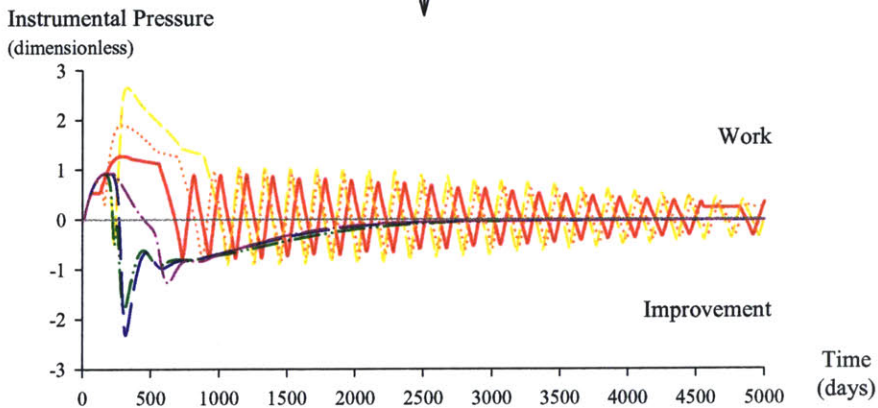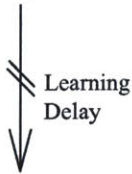
Improvement

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.

Push End (days)	Outcome	Cause of "Better" Throughput	Perceives Positive Covariation	Learned Positive Covariation
10	Failure	Normative Push Ends	No	No
50	Failure	Normative Push Ends	Yes	No
135	Failure	Normative Push Ends	Oscillates to No	Oscillates to No
136	Success	Normative Push Ends	Oscillates to Yes	Oscillates to Yes
200	Success	Yield increase	Oscillates to Yes	Yes
500	Success	Yield increase	Yes	Yes

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

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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 <u>Confounded yet Correct Feedback</u>. 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 <u>Clear Feedback</u>.

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

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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.

Learned Improvement Productivity
(units/(worker-hour))
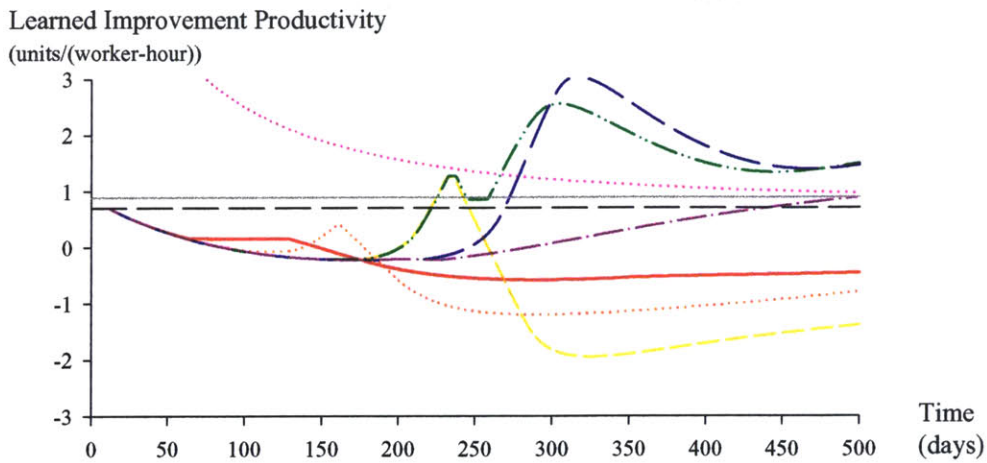
Figure 28. Learned Improvement Productivity over 500 days: Boundedly Rational v. Perfect Process Information

Learned Improvement Productivity
(worker-hours/day)
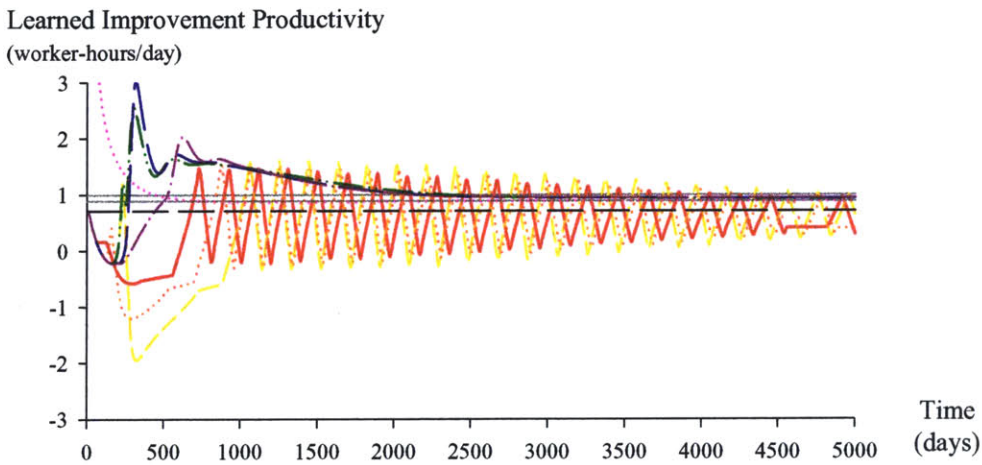
Figure 29. Learned Improvement Productivity over 5000 days: Boundedly Rational v. Perfect Process Information

────── 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

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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

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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 system 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.
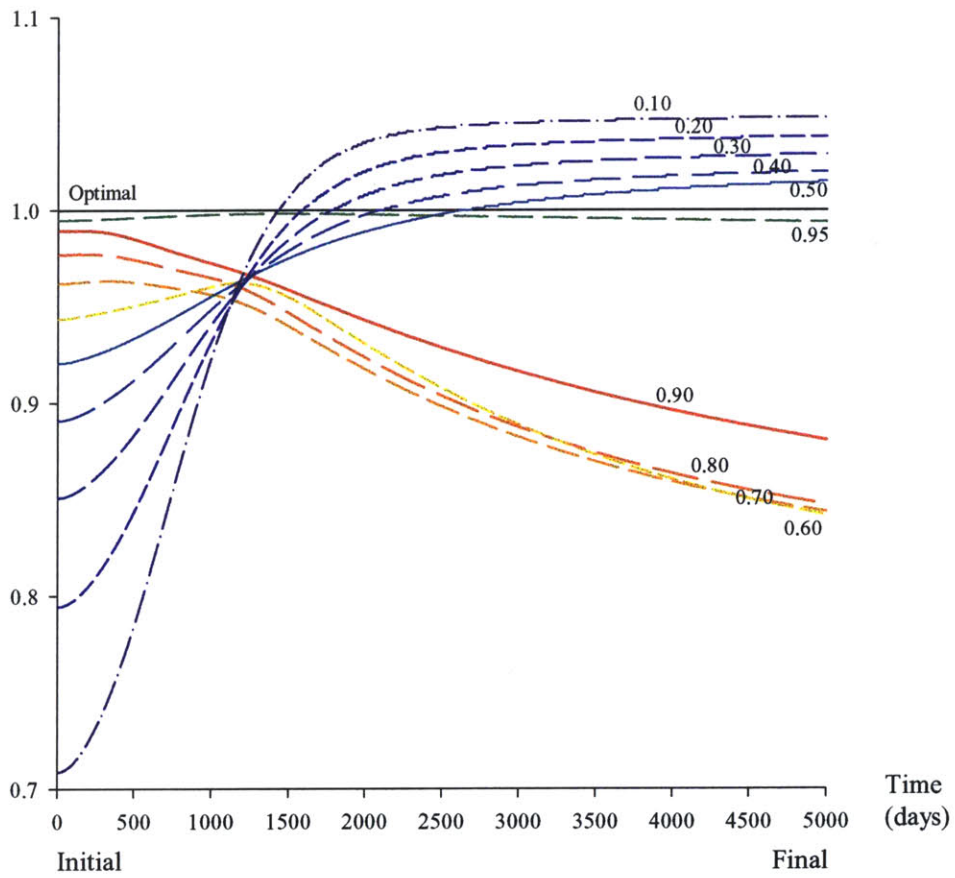
Figure 30. Effect of *Initial Yield* on outcome over 5000 days. Lower *Initial Yield* results in higher final *Yield*. Higher *Initial Yield* results in lower final *Yield*. Very high *Initial Yield* (0.95) stays near *Optimal Yield*. Runs labeled with *Initial Resources to Improvement* values.

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* simulataneously. 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 – <u>Erroneous and Confounded Feedback</u>, <u>Confounded yet Correct Feedback</u>, and <u>Clear Feedback</u> – 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 adversion.

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

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

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

Learning Sector

RI factor	0	1000	100	Guess
T factor	0	1000	100	Guess
Relative Change in T Update Fraction	0.020	0.002	0.010	Reciprocal of Time Constant to Throughput Productivities
Relative Change in RI Update Fraction	0.020	0.002	0.010	Reciprocal of Time Constant to Throughput Productivities
Effect of Information in Difference RI on Update Fraction	0.1	10.0	1.0	Guess
Minimum Time to Change Covariation	10	180	30	Guess

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Appendix 3. Model in Vensim Equation Format

After Push Resources=
        0
        ~   worker*hours/day
        ~ |

range=
        0.02
        ~   DMNL
        ~ |

backlog= INTEG (
        orders,
                initial backlog)
        ~   units
        ~ |

Backlog Pressure Switch=
        1
        ~   DMNL
        ~ |

backlog time=
        10
        ~   days
        ~ |

Below T and RI Update Fraction=
        1
        ~   1/day
        ~ |

Change in Desired Resources to Improvement=
        Normative Change in Desired Resources to Improvement+Instrumental Change in Desired
Resources to Improvement
        ~   worker*hours/day/day
        ~ |

Change in Desired Resources to Work=
        Instrumental Change in DRW
        ~   hours*worker/day/day
        ~ |

Change in Historical RI=
        (Recent RI-Historical RI)/T Historical RI
        ~   worker*hours/(day*day)
        ~ |

Change in Historical T=
        (Recent T-Historical T)/T Historical T
        ~   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(\
        RI Threshold Check,2,4))
~   DMNL
~ |

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)
~ |

Change in IPT from Covariation=
    (IPIPT from Covariation-Learned Improvement Productivity)*Update Fraction for Covariation
~   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)
~ |

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)
~ |

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

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

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

Change in Recent Y=
    (Yield-Recent Y)/T Recent Y
~   DMNL/day

~ |

Defect Rate=
          (1-Yield)*Gross Throughput
          ~   units/day
          ~ |

Desired Resources to Improvement= INTEG (
          Change in Desired Resources to Improvement,
                    Initial Resources to Improve)
          ~   hours*worker/day
          ~ |

Desired Resources to Work= INTEG (
          Change in Desired Resources to Work,
                    Initial Resource to Do Work)
          ~   worker*hours/day
          ~ |

Desired Throughput=
          Initial Throughput*Fraction of Initial
          ~   units/day
          ~ |

Diagnosed Problems= INTEG (
          +Rate of Diagnosing Problems-Rate of Completing Experiments,
                    Initial Problems per Stock)
          ~   problems
          ~ |

Difference RI=
          Recent RI-Historical RI
          ~   worker*hours/day
          ~ |

Difference T=
          Recent T-Historical T
          ~   units/day
          ~ |

Effect of Backlog on Throughput Pressure(
          [(0,0)-(1,100)],(0,1),(1,10))
          ~   DMNL
          ~ |

Effect of Information in Difference RI on Update Fraction=
          1
          ~   day/(worker*hour)
          ~   1 uses tau cov = 100 for t <1000   0.1 uses ErRI for most all times \
                    except briefly early on. Now using 0.5
          |

Effect of T Gap on Pressure(
          [(-1,0)-(1,10)],(-1,0),(-0.492355,0.307018),(-0.259939,0.394737),(-0.0948012,0.657895\

          ),(0,1),(0.15,3),(0.29052,4.95614),(0.480122,7.10526),(0.657492,8.59649),(0.82263,9.64912\

```
              ),(0.828746,9.51754),(1,10))
        ~       DMNL
        ~              |

Entropy Into Undiscoved Problems=
        (Maximum Number of Problems-Total Problems)/Time Constant Due to Entropy
        ~       problems/day
        ~              |

fR Diagnose=
        W Diagnose/Total IR
        ~       DMNL
        ~              |

fR Experiment=
        W Experiment/Total IR
        ~       DMNL
        ~              |

fR Implement=
        W Implement/Total IR
        ~       DMNL
        ~              |

Fraction of Initial=
        0.9
        ~       DMNL
        ~              |

Fraction of Optimal Resources to Improvement=
        Resources to Improvement/Optimal Resources to Improve
        ~       DMNL
        ~              |

Fraction of Optimal Throughput=
        Throughput/Optimal Throughput
        ~       DMNL
        ~              |

Fraction of Optimal Yield=
        Yield/Optimal Yield
        ~       DMNL
        ~              |

Fraction of Problems to Max Number=
        Total Problems/Maximum Number of Problems
        ~       DMNL
        ~              |

Fractional Throughput Gap=
        Throughput Gap/Goal Throughput
        ~       DMNL
        ~              |

frI=
        Desired Resources to Improvement/Total Desired Resources
```

~   DMNL
~ |

frW=
        Desired Resources to Work/Total Desired Resources
        ~   DMNL
        ~ |

Goal RI fraction of Optimal RI=
        1
        ~   DMNL
        ~ |

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
        ~   DMNL
        ~   Hey, that's forrester not foster. Homo Forrester = 1 and Homo Economus = 0
        |

Hours per day=
        10
        ~   hours/day
        ~   length of work 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)\

```
                        ))
        ~       problems
        ~               |
```

Initial Yield=
```
        ((Minimum Yield-Maximum Yield)*(Initial Total Problems/Maximum Number of Problems))+\
                Maximum Yield
        ~       DMNL
        ~               |
```

Instanteous Partial Derivative of Throughput wrt RI=
```
        (Resources to Work*Work Productivity*(Maximum Yield-Minimum Yield)*Improvement
Productivity\
                *Time Constant Due to Entropy)/((Stock Order+((Improvement Productivity*Time
Constant Due to Entropy\
                *Resources to Improvement)/(Maximum Number of Problems*Stock
Order)))^2*Maximum Number of Problems\
                )
        ~       units/(worker*hour)
        ~               |
```

Instrumental Change in Desired Resources to Improvement=
```
        Instrumental Switch*(Max(Min(Pressure on Improvement, range), -range))*Desired Resources to
Improvement\
                /Instrumental Time Constant
        ~       worker*hours/(day*day)
        ~               |
```

Instrumental Change in DRW=
```
        Instrumental Switch*(Max(Min(Pressure on Work, range), -range))*Resources to
Work/Instrumental Time Constant
        ~       hours*worker/day/day
        ~               |
```

Instrumental Pressure=
```
        (Learned Work Productivity-IF THEN ELSE(homo forrester v homo economus switch, Learned
Improvement Productivity\
                , Instanteous Partial Derivative of Throughput wrt RI))/Work Productivity
        ~       DMNL
        ~               |
```

Instrumental Switch=
```
        1
        ~       DMNL
        ~               |
```

Instrumental Time Constant=
```
        50
        ~       day
        ~               |
```

IPIPT from below thRI and below thT=
```
        Learned Improvement Productivity
        ~       units/(worker*hour)
        ~               |
```

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 theorectical 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=

360
~   day
~ |

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*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)<RIThreshold, 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
    ~   worker*hours/day
    ~ |

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

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

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

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

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

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

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

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

Recent T= INTEG (
    Change in Recent T,
        Initial Throughput)
    ~   units/day
    ~ |

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*frI
    ~   worker*hours/day
    ~ |

Resources to Improvement Goal=
        Goal RI fraction of Optimal RI*Optimal Resources to Improve
        ~   worker*hours/day
        ~ |

Resources to Work=
        frW*Resources
        ~   worker*hours/day
        ~ |

RI factor=
        100
        ~   day
        ~   1
        |

RI Rate=
        Difference RI/T Historical RI
        ~   worker*hours/(day*day)
        ~ |

RI Threshold Check=
        IF THEN ELSE(ABS(RI Rate)<RIThreshold, 0, 1)
        ~   DMNL
        ~ |

RI threshold fraction=
        1e-005
        ~   1/day
        ~ |

RIThreshold =
        Recent RI*RI threshold fraction
        ~   worker*hours/(day*day)
        ~ |

Solved Problems= INTEG (
        Rate of Completing Experiments-Rate of Implementing Solutions,
                Initial Problems per Stock)
        ~   problems
        ~ |

Stock Order=
        3
        ~   DMNL
        ~ |

T Diagnose=
        Improvement Time
        ~   day
        ~ |

T Experiment=
        Improvement Time
        ~   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
        ~   problems
        ~ |

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

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\
)
        ~   1/day
        ~   Thresholded Difference RI changed to 1/Thresholded Difference RI
        |

Update Fraction for Covariation=
        Min(Indicated Update Fraction for Covariation,Update Fraction based on Information in
Difference RI\
)
        ~   1/day
        ~ |

W Diagnose=
        Undiscovered Problems/P Diagnose
        ~   worker*hours
        ~ |

W Experiment=
        Diagnosed Problems/P Experiment
        ~   worker*hours
        ~ |

W Implement=
        Solved Problems/P Implement
        ~   worker*hours
        ~ |

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

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