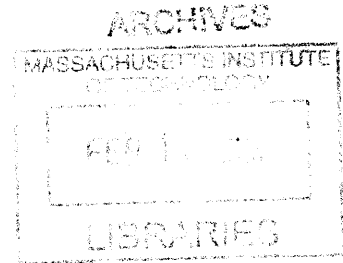


Resistance from Top to Bottom: The Dynamics of Risk Management in Complex Organizations

by

John Landry Lyneis

B.A., Political Science,
Yale University (2001)



Submitted to the Alfred P. Sloan School of Management
in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy in Management

at the

Massachusetts Institute of Technology

September 2012

© 2012 Massachusetts Institute of Technology. All Rights Reserved.

Signature of Author.....
Alfred P. Sloan School of Management
August 24, 2012

Certified by.....
Nelson P. Repenning
Professor of Management
Thesis Supervisor

Accepted by.....
Ezra W. Zuckerman
Professor of Management
Director, MIT Sloan Ph.D Program

Resistance from Top to Bottom: The Dynamics of Risk Management in Complex Organizations

by
John Landry Lyneis

Submitted to the Alfred P. Sloan School of Management
on August 24, 2012
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Management

ABSTRACT

Organizations today devote substantial resources towards the development of governance systems to increase transparency and accountability in areas such as quality, safety, financial accounting, and environmental performance. In this dissertation, I combine ethnographic and simulation methods to understand the implementation and performance of such systems.

In the first essay, I compare the implementation of a safety management system in two industrial plants following accidents. Despite a common process, workers at one plant resist portions of the new system, while at the other plant the system is a relative success. My argument has two parts. First, I argue that resistance to bureaucratic rules is rooted in the lack of involvement that front line actors are afforded in managing anomalies that occur in the application of rules. Second, lack of involvement is more likely to result in active resistance to rules when actors are familiar with one another and with work tasks. While much research emphasizes the benefits of familiarity for performance, I find that actors who are familiar have both the motivation and the ability to resist bureaucratic control, even when rules are designed to serve their own interests.

In the second essay, I extend the findings in the first essay to develop a dynamic theory of the success and failure of governance systems in organizations. Consistent with existing literature, I find that pressure to conform to externally imposed norms of bureaucratic rationality can cause dynamics of gradual decoupling between rules and practice. However, I find that the mechanism by which such pressures operate can be different than previously described. Rather than compelling organizations to adopt practices that are inefficient or opposed to the interests of managers or workers, external pressure creates a conflict that is *temporal*: necessary efforts to demonstrate compliance in the short run directly undermine efforts to make rules effective in the longer term. When organizational actors have the flexibility to build organizational capabilities absent imperatives to demonstrate strict compliance at all times, formal structure can evolve to become a highly effective means of organizing. Absent such flexibility, rules can become a source of conflict characterized by worker resistance, tighter control, and decoupling.

In the third essay, I develop and calibrate a detailed simulation model to illustrate why management efforts to develop capabilities that support governance systems so often fall short. For this essay, I study the case of energy efficiency and maintenance reliability in the built environment. Even where proactive investments would improve both regulated outcomes *and* the bottom line, I show that managers might easily abandon investments early, before crossing a tipping threshold that allows for the realization of full benefits. Thus, successful self-regulation depends not only on managers recognizing and acting on opportunities, but also on managers understanding tipping dynamics and sustaining investments beyond levels that might initially appear sufficient.

Thesis Supervisors:

Nelson Repenning (Chair)

Professor of Management Science and Organization Studies

Susan Silbey

Leon and Anne Goldberg Professor of Humanities, Professor of Sociology and Anthropology

John Sterman

Jay W. Forrester Professor in Computer Science, Professor of System Dynamics and Engineering Systems

Ezra Zuckerman

Nanyang Technological University Professor, Professor of Technological Innovation, Entrepreneurship, and Strategic Management

Acknowledgements

The doctoral program at MIT Sloan has been a wonderful experience. I have grown tremendously both intellectually and personally during my years at MIT, and I wish to thank all of the many people who have made the experience possible.

First, to John Sterman and Nelson Repenning, for welcoming me to MIT and for providing unending support through all stages of the doctoral program. Nelson Repenning provided excellent guidance from my first days in the program, went out of his way to open doors for me at several field sites, encouraged me to develop and pursue my own research interests, and patiently worked with me and provided crucial direction and insight as my initial ideas developed into a full dissertation. John Sterman provided essential vision and direction for the third essay of this dissertation. John held me to the highest standards and pushed me to develop research that has both policy and academic relevance, and models that are fully and carefully justified. Both John and Nelson are wonderful teachers of system dynamics and I feel truly lucky to have had the opportunity to work with them.

When I arrived at MIT I had no idea that I would develop the love and appreciation for sociology that I now hold. I thank Ezra Zuckerman especially for introducing me to the field and for encouraging me to pursue research in sociology and organization theory. Ezra read countless drafts of memos and papers and pushed me to develop my writing skills and to strive for sharp, insightful theories. Susan Silbey inspired me with her enthusiasm for our shared research interests and her dedication to sociology and to teaching. Susan introduced me to many wonderful books and articles and shaped the direction of the research with key comments at each stage. Both Susan and Ezra are dedicated teachers and mentors, and I am also lucky to have learned so much from them.

This dissertation would not have been possible without the generous support of so many people at the field sites where I visited. Numerous operators, mechanics, line managers, and senior managers at Industrial Co. were willing to welcome me at their workplace and take the time to show me around, make me feel welcome, and answer all of my questions. I especially wish to thank JS, JP, and JMS at the corporate organization, JR, BJW, NB, CL, MM at Alpha, and MW, GB, CV, and PA at Beta. Numerous other individuals welcomed me and helped me in ways both small and large. I wish that I could list all of the names here. For my field work at MIT, I wish to thank Peter Cooper, Bernie Richard, Marty Dugal, Joe Gifun, Kevin Connolly, and many others.

I wish to thank also all of the many friends and colleagues that I made during my years at MIT. In particular, my PhD student colleagues made the experience so much more enjoyable. I will miss the many discussions in which we shared research ideas or compared notes about the graduate school process. Gokhan Dogan, Tim Quinn, Joe Hsueh, Kawika Pierson, Jeroen Struben, Dan McCarthy, Ozge Karanfil, David Keith, Jason Jay, Travis Franck, Elisa Alonso, Margaret Stringfellow, Roman Galperin, Michael Bikard, Phech Colatat, and many others were all terrific colleagues.

Several other faculty and staff provided me with guidance and support necessary to navigate the doctoral program. Sharon Cayley made sure that I was always registered for the right classes and met all program requirements. Richard Brewer helped arrange

my funding for my dissertation research. Shiba Nemat-Nasser and Michelle Cole were great resources and I enjoyed seeing them in the office every day.

My choice to pursue a career in system dynamics was not always a given. I thank my parents for introducing me to the field and for supporting all of my career choices along the way. My father was an excellent teacher when I was first learning to model and continues to be a source of modeling wisdom. I also wish to thank Imrana Umar for offering me my first job in system dynamics and for being a great mentor and friend.

Finally, I owe an enormous amount of gratitude to my wife, Zophia, for standing by me throughout this long process. On the many days when the amount of work seemed so daunting and when the end seemed so far away, Zophia listened to all of my frustrations and pushed me to keep going. I thank her for the days and evenings when I could take a break, for taking notes at all of my talks and providing a sounding board for research ideas, and for putting up with me through it all.

Table of Contents

Essay 1 - Choreographed Compliance: Resistance to Bureaucratic Rules in Industrial Plants	9
Introduction	10
Research Site & Methods.....	14
The New Maintenance “Work Control Process”	15
Case selection.....	19
Data Collection	22
Data Analysis.....	24
The Puzzle of Resistance to Bureaucratic Rules	25
Existing Explanations for Resistance to Rules.....	28
Explaining Resistance to Bureaucratic Rules.....	31
Variation in Involvement.....	31
Responses to Anomalies at Alpha: Company Mechanics Resist the WCP Process	33
Responses to Anomalies at Alpha: Operators Extend Resistance to Interactions with Contractors	40
Responses to Anomalies at Beta: Anomalies as a Source of Involvement.....	42
Discussion – Resistance to Bureaucratic Rules	49
Drawbacks of Familiarity.....	51
Familiarity and Employee Involvement	54
Limitations and Future Research	55
References.....	58
Essay 2 - Overcoming the Iron Cage: The Dynamics of Rule Systems in Organizations.....	63
Introduction	64
Theory: Decoupling and the Bureaucratic Form of Organization.....	67
Research Site & Methods.....	75
The New Maintenance “Work Control Process”	76
Case Selection	81
Data Collection	83
Data Analysis.....	85
Overview of the Two Initiatives.....	87
The Work Control Process at Alpha	87
The Work Control Process at Beta.....	93
A Model of Rule Implementation.....	98
The Basic Structure of Organizational Control.....	99
Expanding the Model: First and Second Order Improvement.....	102
The Dynamics of Decoupling: The WCP Process at Alpha.....	111
Extending Decoupling: Front Line Deviance and Resistance	115
Tightening Control.....	122
Successful Implementation at Beta: Building Worker Involvement.....	125
Building Involvement.....	128
Problems as Source of Participation.....	131
Loosening Control.....	136
Discussion	139

References.....	145
Essay 3 – Giving up Too Soon: The Failure of Win-Win Investments in Process Improvement and Industry Self-Regulation.....	151
Introduction	152
Research Setting & Methods	156
Methods.....	158
A Model of Building Maintenance & Energy Usage.....	160
Maintenance Staffing & Work Orders.....	160
Sources of Work Orders: Equipment Defects	163
The Sources of Defects: Infrastructure Renewal	166
Building Energy Use	168
Model Analysis.....	172
Simulating a Proactive Investment in Maintenance.....	172
Crossing the Tipping Point: The Impact of Investment Size & Duration	175
Reinvesting Energy Savings.....	179
Sensitivity Analysis: The Strength of Positive Feedback	181
Discussion & Conclusion	185
References.....	191
Appendix – Technical Documentation for Essay 3	196
Maintenance Work Orders and Defects Structure	196
Collateral Damage Matrix	196
Hazard Rates and Time Constants for Building System Categories	196
Allocating Proactive Work Among Building System Categories.....	197
Infrastructure Renewal Structure	198
Resolving Right-Censoring in Individual Building System Data.....	198
Allocating Renewal Dollars Among Items	199
Building Energy Consumption Structure.....	200
Results of Panel Regressions on the Effect of Aging on Energy Use	200
Estimating τ and E^* :	205
Allocating Potential Energy Savings Among Items.....	209
Implementing a Proactive Investment.....	210
Financial Calculations	211
Diagrams of Model Sectors	211
Building Renewal Sector.....	212
Prioritization of Renewal Items.....	213
Energy Requirements from Buildings.....	215
Equipment Defects and Elimination	216
Defect Creation	217
Work Order Backlog	219
Maintenance Staffing	220
Maintenance Budget	222
Maintenance Spending.....	223
Calculating the NPV of Investment.....	223
Complete Listing of Model Equations	225

Essay 1 - Choreographed Compliance: Resistance to Bureaucratic Rules in Industrial Plants

Abstract

Organizations today devote substantial resources towards the development of governance systems to increase transparency and accountability in areas such as quality, safety, and environmental performance. In this study, I use ethnographic methods to compare the implementation of one such system - a safety management system - in two industrial plants following accidents. Despite a common process, workers at one plant resist portions of the new system, while at the other plant the system is a relative success. I find that resistance in one plant is made possible by the familiarity that actors have with one another in regulated work interactions. While much research emphasizes the benefits of familiarity for performance, I find that employees who are familiar at times have both the motivation and the ability to resist bureaucratic control, even when rules are designed to serve their own interests. Thus, to successfully channel behavior and manage risk, organizations must introduce novelty into work interactions and allow expert actors greater interpretive flexibility to manage anomalies ungoverned by the rule system.

Introduction

In an era of ever-increasing technological progress and recent large scale disasters, managers and regulators today devote considerable attention to the problem of managing risk. Central to their efforts is the view that if rules are clear, compliance is documented, and actors are held accountable through a transparent audit process, important risks can be controlled (Power 1997, Coglianese & Nash 2001, Huising & Silbey 2011). The “audit explosion,” as Power (1997) describes it, is especially prominent in areas such as financial accounting, environmental management, and workplace safety. Yet, despite the proliferation of these strategies, we continue to see serious lapses due to non-compliance or under-enforcement of rules.

Why do organizational actors sometimes fail to follow rules? Broadly speaking, at least three explanations exist. First, rule breaking may be a form of deviance designed to harm the organization or resist management control. Individuals may resist a rule that they believe is applied unfairly (Tyler & Lind 1992), or groups of employees may resist rules that they view as threatening to their autonomy (Eldridge 1968, Adler & Borys 1996, Morrill et al 2003). Second, rule breaking may be *pro-social*, with the goal of advancing the organization’s interests (Morrison 2006, Canales 2011). Actors may believe that a rule is counter to the organization’s true interests, and that managers will therefore choose to amend the rule, rather than punish those who deviate, when the discrepancy is discovered. Finally, in cases where rules are designed to protect vulnerable employees from harm, actors may avoid compliance because they fear retaliation (Kellogg 2009). In such cases, actors once again recognize that a rule is

counter to the organization's unstated interests; however, the discrepancy is believed to be a result of decoupling (Meyer & Rowan 1977) rather than ignorance.

Consider, however, the case of an organization that has recently suffered an adverse event, with harm to either the organization's reputation or to the bottom line. Such an event may be an ethical lapse, a product recall, or an accident causing injury to workers. In the wake of such an event, we would expect organizational actors to comply with rules that reduce the risk of future events, and senior managers to both support and enforce such compliance. Yet, even in the face of recent failure, organizations may struggle to implement risk management systems designed precisely to learn from that failure (Huisling & Silbey 2011). Why?

In this study, I consider one example of the above phenomenon: the case of workplace health and safety following an accident. Industrial Co (a pseudonym) is a large corporation with multiple plants. In recent years, in response to a number of accidents involving injuries to workers across several of Industrial's plants, plant managers have placed a renewed emphasis on safety. Thus, while ordinarily safety rules may become decoupled from managers' true production motives, here such ambiguity is reduced. In addition, injuries to peers have increased the awareness of the workforce to the risks of work. Yet, despite such an alignment of interests, Industrial has struggled to implement portions of a new system of rules and procedures designed to improve safety.

Several studies note that organizations often fail to learn from failures (e.g. Baumard & Starbuck 2005, Vaughan 2005b). However, such work typically attributes the failure to adopt new rule systems to the three explanations listed above, and thus cannot explain the failed implementation of simple, widely understood safety rules that

have known benefits. For example, organizations may overly attribute accidents to exogenous or idiosyncratic forces (Starbuck 2009) or to operator error (Perrow 1983), leading to rule systems that are poorly designed or that unnecessarily infringe on autonomy. In addition, organizations may implement rules to satisfy external audiences (Edelman 1992) yet fail to make the necessary structural, political, and cultural changes to support actors in using those rules (e.g. Vaughan 2005b, Kellogg 2009). When rules are accurate, supported by top management, subject to revision and improvement, and part of a control system that values front line expertise where responses can't be scripted (Weick, Sutcliffe & Obstfeld 1999; Perin 2005; Vaughan 2005a), we would expect front line support. Why, then, are such rules not always implemented?

This paper draws on such a case to develop inductively a theory of resistance to rules in organizations. Following a description of the research site and methods, I document the empirical puzzle. Prior to each maintenance job, unit operators and maintenance mechanics are required to “walkdown” the physical job location and have a conversation related to job risks. Walkdowns have clear safety benefits, as acknowledged by both the industry and the academic literature on safety and reliability, and are also supportive of front line expertise. First, by bringing together individuals with different functional expertise (operations and maintenance) in the presence of a physical boundary object (Star & Griesemer 1989; Carlile 2002), walkdowns provide a forum to transfer knowledge related to job risks that might otherwise be lost. Second, walkdowns can surface anomalies and “interrupt routines” (Silbey 2009), thereby facilitating the enforcement of rules and limiting the normalization of deviance (Vaughan 1996). Finally, walkdowns can increase the voice of front line actors by serving as a

coordination mechanism to discover and jointly raise doubts. Yet, despite these numerous benefits, during a period of ethnographic observation at one of Industrial's plants (labeled Alpha), workers complete walkdowns less than half of the time. In contrast, at a second plant (labeled Beta), the rule is followed far more frequently.

The remainder of the article is devoted to explaining these divergent outcomes, and the puzzling nature of failed compliance at Alpha. The argument has two parts. First, I argue that resistance to bureaucratic rules is rooted in the *lack of involvement* that front line actors are afforded in managing anomalies that occur in the application of rules. By design, bureaucratic rules limit the discretion of front line actors. While such limits are often necessary to control risk and ensure actors' own safety, in the case of errors or exceptions, actors expect to be involved in their resolution. Such involvement is especially lacking at Alpha.

Second, lack of involvement is more likely to result in active resistance to rules when actors are *familiar* with one another and with work tasks. Familiarity – defined as local task knowledge and embedded work relationships (Katz 1982; Espinosa et al. 2007) – is a source of resistance for two reasons. First, actors who possess local knowledge of work locations and work tasks are more likely to interpret inflexibility in the face of anomalies as a challenge to expertise and dignity (Hodson 2001). Second, social relationships between familiar actors allow actors to coordinate resistance. At Alpha, the physical co-location between operators and some mechanics allowed such resistance to develop. Thus, despite the many benefits of local task experience and embedded relationships for performance (Reagans, Argote & Brooks 2005; Espinosa et al. 2007), familiarity may also at times *hinder* coordination and *weaken* compliance.

The tension between bureaucratic rules and involvement in the context of embedded relationships is not a new theme in organization studies (e.g. Heimer 1992). Yet, while past work acknowledges that a lack of involvement can lead to alienation and resistance (e.g. Freeland 2001), the specific effect of involvement has been difficult to isolate because it is often conflated with the effect of rule content. That is, where front-line actors expect involvement, the main goals of standardization also work against the interests of workers or their clients (e.g. Lipsky 1980, Orr 1996). Here, both the walkdown rule and the broader system that it supports unambiguously reduce risk and increase workplace safety. The failure of bureaucratic control even under favorable circumstances highlights the challenges of modern efforts to manage risk.

Research Site & Methods

The research strategy employed in this article is to draw on a combination of ethnographic observation, semi-structured interviews, and archival data for the generation of grounded theory (Glaser & Strauss 1967). I begin with a brief description of the sites, followed by more details regarding case selection, data collection, and analysis strategies.

For many reasons, industrial plants are excellent sites to study the management of risk through bureaucratic rules. To start, plants in the industry that we study are highly hazardous work environments. Workers face risks due to heavy machinery, hot surfaces, and exposure to dangerous chemicals.

Although hazardous, plant operations are highly stable and are based on technologies that have been in use for decades. As a result, plants have evolved to exhibit many of the features of the classic bureaucratic form (e.g. Scott 2003), including

strong hierarchical control, written rules, and a division of labor based on specialized knowledge. Knowledge is highly specialized and local: most operators and line managers have years of experience working in a specific unit, and can recognize by sound and smell when a piece of equipment is not running correctly

In response to several accidents, Industrial recently introduced a host of changes to reduce the risk of future accidents. Most notably, the company developed and implemented a comprehensive “safety management system” to cover all aspects of operations. Management systems are at the forefront of recent efforts to control risk, and have become standard practice across a number of industries, particularly in the areas of safety and environment (Coglianese & Nash 2001, Huising & Silbey 2010). In this paper, I focus on one particular component of Industrial’s management system: the new process to manage the risks of maintenance work. The new process, named the “work control process” (WCP), was developed over a period of several years by the central corporation, and rolled out to all of the company’s operations in several iterations. At the time of observation, implementing and improving the WCP process remained a major focus for much of the company.

The New Maintenance “Work Control Process”

Maintenance work is a substantial hazard and has been the source of several recent events in the industry. Maintenance work is performed by hourly maintenance mechanics, many of which are contractors. Typical maintenance jobs include inspecting and repairing pumps, compressors, valves, pipes, and tanks that transport and hold

material. Accidents can occur when equipment is not correctly prepared for maintenance, or when there are miscommunications surrounding the nature and location of work.

The new process for maintenance work, named the “work control process” (WCP)¹, is designed to ensure that risks are evaluated and safe practices are followed for every maintenance job. For reasons stated above, the walkdown requirement is a central feature of the WCP. In addition to the walkdown, WCP includes a substantial emphasis on the planning and risk assessment of work. Under the previous process for maintenance work, mechanics were sent to units as needed, and operators and front line supervisors created risk assessments on the spot (with the involvement of managers and safety experts for higher risk work). Under WCP, the process is far more formalized. Figure 1 illustrates the process for a typical maintenance job. Now, jobs are broken into individual tasks and risk assessments are created for each task as much as a week ahead of time, following specific rules. Managers must sign off on all work, with higher-level approvals required according to the level of risk. By the time of the walkdown, operators and mechanics should have a risk assessment that is tailored to the specific job, approved by managers, and that reflects all relevant safety rules.

¹ The name “WCP” is a pseudonym

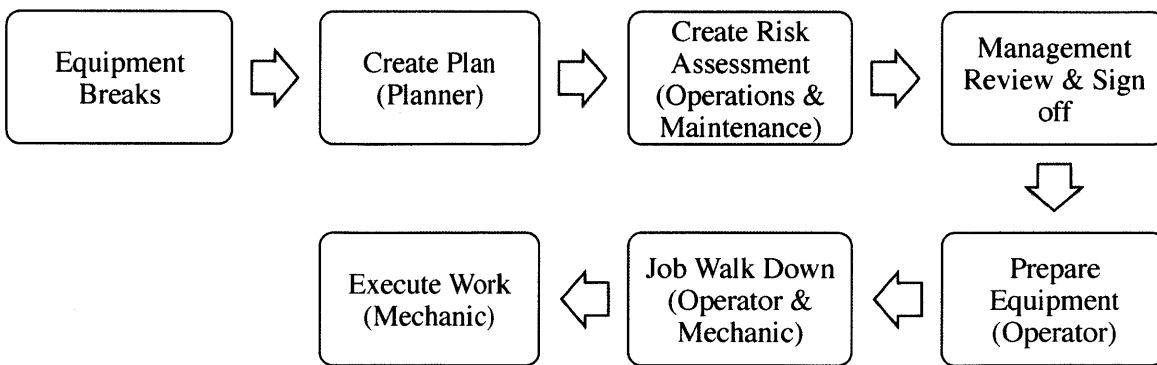


Figure 1: The Work Control Process (WCP)

The WCP process, and especially the walkdown component, matches the prescriptions of both the practical and academic literature on managing risk. According to research in psychology, individuals are notoriously bad at judging risk (Slovic 1987). In work settings, actors are especially vulnerable to the “normalization of deviance” (Vaughan 1996). When actors notice an anomaly, they may conclude that the anomaly is an acceptable risk, and decide to proceed with work. Because very often anomalies do not result in accidents immediately, actors learn, sometimes incorrectly, to reclassify the anomaly as a ‘normal’ occurrence. Eventually, the same anomaly that is now normalized could lead to an accident.

The WCP process works to cut short the process of normalization. When detailed rules are enforced during walkdowns, actors lose the discretion to redefine anomalies as normal (Vaughan 2005a). Rules are established independently of local work cultures, and remain relatively consistent across time and place. To promote such consistency, rules are controlled by an independent corporate function, and interpreted by an independent safety group in each plant. Plants are also subjected to periodic audits to

assess compliance. Table 1 lists several examples of controls that might be identified in risk assessments, listed on permits, and verified during walkdowns. All of these practices are widely recognized to reduce the risk of an accident. Although operations managers may still advocate adjustments to rules to fit local conditions or particular situations, the WCP process is designed to limit such influence.

Risk	Typical Controls
“Breaking Containment” : Opening up a pipe, creating risk of exposure to substances	“Isolate” the point by shutting off flow, drain, test to be sure empty
“Spark Potential” : Devices such as power tools, vehicles may create a spark, igniting any hazardous gases in the area	Gas test area prior to work
“Working at Heights”	Install scaffolding, wear harness, barricade area below
“Confined Space Entry” – risk that air inside confined space is not sufficient to breathe	Gas test prior to entry, hole watch, rescue plan, wear respirator
Working with Tools	Be aware of pinch points, wear gloves

Table 1: Example Safety Risks and Controls

In addition, the process works at the ground level to elevate anomalies that might otherwise be noticed only by the front lines. Risk assessments function very much like “checklists,” prompting actors to notice anomalies that they might otherwise miss. Checklists have been shown to reduce the rate of mistakes and accidents in a number of settings, such as hospitals (Haynes et al 2009). In addition, when actors are prompted to report and correct anomalies rather than normalize them, the organization can learn. Spear (2009), for example, describes how high performing organizations rely on front line actors to report deviations from standard practice. Front line actors have access to

unique knowledge, and effective organizational learning depends on creating conditions where actors are able to share such knowledge (Tucker & Edmondson 2003). By providing clear rules and a structured environment to notice deviations from those rules, the WCP process should contribute to improved safety and reliability.

Case selection

Although the WCP process is well designed to improve the safety and reliability of maintenance work, Industrial has experienced substantial variation in the success of the policy across all of its plants. Here, I exploit such variation to explain resistance to rules, particularly rules designed to promote social goals such as workplace safety. Specifically, I compare the experience of two plants, labeled Beta and Alpha.

A comparison between two plants from the same corporation has many advantages over existing literature on workplace safety specifically, and self-regulation and bureaucratic control more generally. First, such a comparison controls for technology. Technology is an important consideration in existing research on risk and accident in organizations. Perrow (1984) argues that technology – specifically the degree of coupling and complexity of interactions – determines an organization’s vulnerability to normal accidents. Likewise, Vaughan (2005a) argues that the certainty of technology influences the control systems that organizations can develop to limit the normalization of deviance. Technology may also influence the importance that actors place on safety. Given identical technologies, differences in the implementation of rules cannot be explained by differences in the degree of hazard of work.

Second, comparing two plants from the same company controls for the nature of the rule system itself. As noted, both plants are implementing an identical process. The specific design of rule systems can have a large influence on implementation outcomes. For example, Edelman (1992) argues that when rules are ambiguous, contain weak enforcement mechanisms, and emphasize procedures rather than outcomes, symbolic compliance is more likely. Here, the two plants are identical on these dimensions.

Third, the comparison here controls for the regulatory and institutional environment. Beta and Alpha both face similar pressures from the corporate organization to implement the mandated WCP process, including periodic corporate audits. In addition, both plants face similar pressure from government regulators. Past research illustrates that the manner of regulatory enforcement influences the success of self-regulation (e.g. Short & Toffel 2010). Both Beta and Alpha were historically poor performers in the areas of health and safety, and both have made substantial progress in recent years on a number of safety metrics, including accident rates and equipment reliability (driven by a substantial investment in infrastructure at both sites).

Table 2 summarizes the similarities and differences between Beta and Alpha. In addition to the areas already noted, efforts were made to control for a number of other factors, including the presence of a union, and the use of contract maintenance mechanics. Table 2 also notes a number of differences between the two plants. Notably, Alpha is larger, has a slightly higher use of company mechanics, and made a number of different choices related to WCP implementation. I provide a more complete case study of each plant's implementation effort elsewhere (Lyneis, second essay in this dissertation). The full context of each plant's implementation is necessary to understand

why worker involvement was higher at Alpha than at Beta. In this paper, I focus on the consequences of weak involvement as a source of worker resistance.

	Alpha	Beta
Location	Outside urban center in U.S.	Outside urban center in U.S.
Technology	Industrial Plant, organized into process units	Industrial Plant, organized into process units
Work organization	Hierarchical	Hierarchical
Size of plant	Three times x	x
Use of contractor labor	Extensive (somewhat less so than Beta)	Extensive
Existence of Safety Department	Yes	Yes
Local Mgmt support for new WCP process	Strong – top priority beginning in August 2010 (somewhat lower priority earlier)	Strong – top priority beginning in December 2009 (somewhat lower priority earlier)
Timeline of WCP Implementation	Several iterations over 2006-2011	First iteration in 2006; Second in December 2009
Regulatory Environment	Strong pressure from government regulators	Strong pressure from government regulators
Past Safety record	Poor – significant improvement 2007-2011, including large infrastructure investment	Poor – significant improvement 2007-2011, including large infrastructure investment
Union status	Unionized	Unionized
Organization of maintenance	Mixed – some company mechanics are co-located with operators	Centralized – mechanics are not assigned to individual units
WCP staff structure	Hourly operators switched to day roles to write permits	Additional management positions added to write & approve permits
WCP format	Computer based (switch to computer based in 2009)	Paper based

Table 2: Comparison Between the Two Plants

Data Collection

As indicated above, data collection consisted of a mix of ethnographic observation, semi-structured interviews, and gathering of some archival documents. During initial visits to Beta in May 2010 it became clear immediately that implementation of the WCP process was the major focus of the organization, and that the opinion of the front lines was not always favorable. As such, I made efforts to collect a range of data to understand the perspective of both management and the workforce. In total, I spent seven weeks onsite at Beta between May and September of 2010. I spent more than 100 hours shadowing front line operators and maintenance mechanics (company and contractor) during day shifts, with an emphasis on the morning hours when the majority of maintenance work begins and the handoff between operations and maintenance occurs. To capture a broad cross section of the plant I shadowed in 5 different operations areas. (Although there were differences between the areas in the demographics of the workforce and the management style of unit superintendents, the patterns relating to behavior on walkdowns were broadly consistent). While shadowing, I engaged in numerous informal conversations with individuals whom I met – these conversations often lasted 30 minutes or more, and were generally highly valuable. Generally, the pace of work provided ample opportunity to ask employees for explanations and interpretations of events either during or directly after their occurrence. To gain the trust of the workforce, I did not take notes while shadowing, but jotted notes during breaks and wrote full-length narratives each evening before returning to the field.

As noted, Beta began implementation of the revised version of WCP in December 2009, five months before the period of observation. To learn about the history of the

policy and expand on observational data, I supplemented observation with more than 50 semi-structured interviews, half of which were with hourly employees (including operators, company mechanics, and contractor mechanics). Most interviews lasted around an hour, and the majority were recorded and transcribed. In addition to asking participants to describe the overall timeline and process of implementation, I asked participants to describe particular problems that they experienced while working within the WCP process, and how those problems were then resolved. Finally, to gain the management perspective, I attended more than 20 staff meetings and interviewed salaried employees from all functional areas.

	Alpha	Beta
Hours of Direct Front Line Observation	~100 (+50 hours of risk assessment meetings)	~100
Actors Shadowed	Operators, Maintenance Mechanics, Safety specialists	Operators, Maintenance Mechanics, Safety specialists
Number of Interviews	15	~50
Actors Interviewed	Managers, Safety Managers	Managers, engineers, operators, mechanics, Safety Managers
Weeks on Site	10 (January – June ‘11)	7 (May – September ‘10)

Table 3: Data Collected at the Two Plants

I pursued a similar strategy at Alpha. I spent 8 weeks on site between January and June of 2011; in addition, I made shorter visits of a few days each in March of 2009 and September of 2010. In total, I spent a similar period of time – more than 100 hours - shadowing front line operators and mechanics (both contractor and company), again focusing on the handoff between operations and maintenance, and once again incorporating several different process units. In addition, I observed more than 30

separate risk assessment meetings involving an operator, a mechanic, and a safety expert, and interviewed 15 line and safety managers. Table 3 summarizes data collected at both plants.

Data Analysis

Data were analyzed using standard methods of grounded theory building (Glaser & Strauss 1967). Observational data and interview transcripts, including notes compiled following all informal conversations, were assembled in Atlas/ti, a qualitative data analysis program. Analysis proceeded along several directions.

First, I coded interviews and informal conversations for all statements related to the implementation of WCP, including positive endorsements, recurring problems, and the timeline of management strategies or adjustments. I used this information to construct a case narrative for each site. Second, given the prevalence of implementation problems, I coded more specifically for the occurrence of problems, anomalies or disagreements, especially between rules and work conditions or between rules and the opinions of actors. I also noted how these issues were resolved, if at all, and identified patterns of responses.

Early on, it became clear that the handoff between operations and maintenance is a crucial interaction that drives the WCP process, and is a point where many anomalies are surfaced. As a result, I made a list of all handoffs encountered during observation, any problems that occurred during these handoffs, and categorized how those problems were resolved. I coded all handoffs according to whether a physical walkdown occurred: had the operator and mechanic signed the form at the operator's desk in the shelter, or did they meet at the actual job site? If the actors met at the job site, was there a discussion

about job risks, or did the operator simply sign the form and move on? I also noted the identity of the mechanic (contractor or company), and where possible, a description of the work. I used the job descriptions to categorize work according to the level of risk, using the organization's official classification scheme, as listed in written documents. (When a walkdown did not occur, it was not always possible to obtain an accurate description).

In the final stage of analysis, I attempted to piece together the detailed observational data within the broader case narratives. Given the differences that emerged between the two plants in the patterns of responses to problems or anomalies, I made a list of both structural features of the plants and management strategies that might have influenced the divergence. The list that emerged confirmed the importance of the co-location of company mechanics. I expand on these points in the analysis and discussion sections.

The Puzzle of Resistance to Bureaucratic Rules

The results of the analysis of job walkdowns are presented in Table 4. Over an equivalent period of 100 hours shadowing a mix of front line operators and mechanics at both plants, variance between the two plants is clear. At Alpha, walkdowns with full compliance are performed 40% of the time, whereas at Beta the figure is 93%. As noted above, I code full compliance when a physical walkdown occurs that includes a discussion of job risks. At Beta, several jobs did not require walkdowns because operations managers had previously walked these jobs out. (In an attempt to increase the efficiency of handoffs, Beta revised the policy to allow managers to handle some walkdowns). The difference between the two plants is especially noticeable for medium

and low-risk work: actors at Beta always walkdown such work, whereas the rate for such work at Alpha is only 33%.

	Alpha					Beta				
	Jobs	Jobs Requiring Walkdown	Physical Walkdown	Walkdown with Discussion	Percent Walkdown & Discussion	Jobs	Jobs Requiring Walkdown	Physical Walkdown	Walkdown with Discussion	Percent Walkdown & Discussion
Total	43	43	22	17	40%	18	14	13	13	93%
Contractor	33	33	20	16	48%	15	11	10	10	91%
Company	10	10	2	1	10%	3	3	3	3	100%
High Risk	8	8	8	7	88%	5	5	5	5	100%
Medium Risk	11	11	5	3	27%	4	4	4	4	100%
Low Risk	10	10	5	4	40%	8	4	4	4	100%
Risk Unobserved	14	14	4	3	21%	1	1	0	0	0%

Table 4: Comparison of Walkdowns Observed at Alpha and Beta

A strong qualitative difference also exists between the two plants. At Beta, when a mechanic enters the operations shelter to sign in to begin work, he is usually greeted right away. Operators know what work is scheduled for the day, and quickly confirm that the mechanic's assigned job matches what is on the schedule. The two then walk to the job location and discuss the work. Usually, there is considerable back and forth while the operator learns exactly what the mechanic proposes to do. What is the sequence of tasks? For example, if a crane will be used to lift out a piece of equipment, where will the crane be located? What path will the lift follow through the air? Is the mechanic aware not to lift over any dangerous process lines that are nearby? If equipment has been disconnected for the job, the operator will also press the "on" switch in the mechanic's presence to verify that the equipment cannot be re-energized while the crew is working. Very often, the operator asks the mechanic whether he is comfortable with the work, and offers to help should anything arise. When mechanics are company mechanics, the

discussion may be shorter and involve less explanation, but a walkdown still occurs. Finally, after all questions are answered, the pair returns to the operations shelter to sign the work permit.

At Alpha, the handoff between operations and maintenance looks far different. To start, there is a notable difference between the interaction when the mechanic is a contractor and when the mechanic is a company employee. When company mechanics arrive in the operations shelter, operators will usually glance at the work permit only briefly, sign, and send the mechanic on his way. Sometimes, mechanics will linger to chat about company politics, hobbies, or recent incidents or policy changes. From time to time, a job will require that an operator perform a “gas test” to ensure that the work area is clear of flammable vapors that could be ignited by sparks created during work. On these occasions, the operator will walk to the job site, quickly take a reading, sign the permit, and return to the shelter. If a question later comes up that the mechanic cannot answer alone, he will either call the operator on the radio or return to the shelter. At that point, a more thorough discussion may occur.

At Alpha, when mechanics are contractors, the interaction is different still. When contractors enter the operations shelter, they often have to wait to get attention. A contractor may stand for several seconds before an operator says, “can I help you,” without taking his eyes off his computer. Answers to questions are brief and operators perform only those duties that are required. For example, if a question emerges about a work permit, the operator may send the mechanic away rather than call his own boss on the phone to clarify. The operator will then ask the mechanic: do you need me to walk it out? If the answer is yes, the two will walk out to the job site. At this point, a short

discussion will ensue that covers several scripted points, corresponding to specific requirements. If the job requires entering a confined space, is the “hole watch” present? Does the crew know where the nearest safety shower is in the event of a chemical spill? Especially for medium and lower risk work, the operator rarely asks about the content of work. As such, although a discussion occurs, it is often choreographed to meet only minimum requirements.

Existing Explanations for Resistance to Rules

As noted in the introduction, the failure of actors to fully adopt the walkdown practice at Alpha is surprising, and is not well explained by existing theories of rule behavior in bureaucratic organizations. The puzzle is especially surprising given that actors at Beta have adopted the practice, despite facing similar job risks, a similar pace and nature of work, and similar rule content. Below I consider two existing explanations for rule non-compliance: (a) workers view the walkdown rule as poorly matched to situated demands, and (b) workers fear retaliation from practicing walkdowns. I argue that neither of these explanations can fully explain the failure of rules at Alpha.

First, actors may resist rules that fail to match the situated demands of work. For example, Orr (1996) describes how formal procedures fail to incorporate many of the practices that repairman actually use to fix broken machines. Likewise, Lipsky (1980) argues that “street level bureaucrats” facing large caseloads and diverse client needs cannot possibly apply rules consistently. Canales (2011) points out that front line actors with local knowledge may discover opportunities to deviate that are in the organization’s interest.

The walkdown rule does not match the description of a rule where such deviations should ever be warranted. In fact, the walkdown rule has value precisely because all contingencies can never be planned. In theory as well as in practice, walkdowns serve to uncover problems or anomalies and give actors a voice in resolving them. At both plants, I observed anomalies occur in approximately 35% of all job interactions – 7 out of 18 at Beta, and 15 out of 43 at Alpha. (Anomalies could include errors on job permits, problems with the preparation of equipment, or problems with the planned work sequence). In addition, as examples below will illustrate, very often anomalies require input from both parties in order to be resolved.

Walkdowns are also designed to enforce work practices that workers support and practice without question. Given the hazardous nature of work in these plants, strict adherence to protocol is a fact of life. Consider the task of unbolting a valve from a pipe – a typical task performed by pipefitters many thousands of times during their careers. When company pipefitters arrive at a jobsite to unbolt a valve, they first check to see that the pipe is empty by tracing the line backwards to locate the point where the flow is blocked. According to protocol, an additional valve must be locked ‘open’ at some point in order to prove that the line is in fact empty. (Operators are responsible for leaving the equipment in this state). Mechanics next inspect this additional valve, and stick a rod into it to ensure that flow is not blocked by sediment. Once it is absolutely clear that the line is free of material, unbolting can begin. Mechanics first loosen alternate bolts, before finally cracking the pipe open on one side, so that it can be closed quickly if necessary. These same steps are performed consistently every time a pipe is unbolted.

Notably, many of these checks are exactly those that are codified as rules and are designed to be a point of discussion on walkdowns.

A second possible explanation for failed compliance is that actors fear retaliation. Often, safety programs - much like other programs designed to protect the rights of vulnerable employees (e.g. Edelman 1992, Edelman et al. 1993, Dobbin & Kelly 2007, Kellogg 2009) - come at the initiative of professional safety departments and are never fully endorsed by line managers, who may sense threats to their status or to the bottom line (Hall 1993). Historically, safety has also been a major focus of worker solidarity and labor union activity (Reid 1981, Rees 1988). As such, workers may fail to adopt walkdowns because they feel pressured by managers to avoid the practice. For example, Kellogg (2009) describes how a similar handoff between employees becomes the focal point for resistance to a new rule in a surgical residency program: at one hospital, junior employees who perform the handoff as required become the victims of retaliation.

Observation at both plants, however, suggests that retaliation cannot explain failed compliance. Top managers at both plants have made adherence to the WCP process a major priority. In addition, in my observation operators and mechanics generally had ample time to complete the practice, and were never discouraged by immediate supervisors from doing so. Outside operators typically complete rounds and other duties prior to the start of maintenance, and mechanics must inspect job sites prior to work in any case.

Explaining Resistance to Bureaucratic Rules

I argue that resistance to the walkdown practice at Alpha is part of a broader pattern of resistance against the WCP process. To understand the sources of such resistance, I compare observational data across four subsets of job interactions: operators and company mechanics at Alpha, operators and contractor mechanics at Alpha, operators and company mechanics at Beta, and operators and contractors at Beta. As noted, these interactions represent opportunities for actors to discover and correct problems or anomalies that arise during work. As such, I analyze the data for patterns in how actors respond to problems or anomalies. What kinds of anomalies occur and how are they resolved or not resolved? These patterns provide important insights into sources of resistance.

Two main findings emerge. First, I observe variance in the level of *involvement* that actors are afforded in response to anomalies. While actors at Beta often use their expertise to participate in resolutions to anomalies, actors at Alpha instead find that their participation is limited. Anomalies are either not resolved, or solutions are imposed in some manner. Second, the familiarity of actors interacts with involvement to have an important influence on the responses that actors pursue. At Alpha, the co-location of company mechanics and operators is a reason why actors in such interactions respond to a lack of involvement by actively resisting the walkdown rule.

Variation in Involvement

By design, the WCP process limits the involvement of front line actors. To control risk, standard rules are imposed on maintenance work and the discretion of front line actors is limited. Job plans and risk assessments are created days in advance by

trained experts, and must be approved by managers. Actors are expected to implement all steps so that risks are controlled as planned, and may not improvise in ways that might introduce risk.

When jobs unfold as planned, the process is highly effective. As noted above, most standard safety practices are not controversial and are followed routinely. In my observation, however, many problems occur in inevitable cases when plans fall short. Job risk assessments may contain errors, the job scope might change, exceptions occur, or mechanics may discover that they require an additional step or tool to complete the work. In such cases, the lack of flexibility built into the process becomes a challenge: risk assessments must be recreated, and managers located to re-approve the work. Front line actors observe these problems and expect to be involved in the process of interpreting anomalies or re-aligning work with risk assessments and job plans.

Across interactions at both plants, I code whether responses to anomalies afford actors such involvement. Three common responses build involvement: explaining & correcting, discussion & joint interpretation, and challenging authority. Two responses preclude involvement: submitting to authority, and active deviation. Table 5 compares the incidence of these responses across the two plants. In an equivalent period of observation between the two plants, actors at Alpha find their involvement cut short far more frequently. In a separate paper, I elaborate on this finding and explore the reasons why involvement is stronger at Beta than at Alpha. Simply put, involvement requires a balance between the number of problems that are surfaced and the resources of the organization to resolve those problems and develop routines that support compliance.

Due to a number of features of Alpha’s implementation effort, such a balance was often not achieved.

Responses to Anomalies	Alpha	Beta
<i>Responses that Build Involvement</i>		
Explaining & Correcting	2	3
Discussion & Joint Interpretation	4	3
Challenging Authority	1	1
<i>Responses that Preclude Involvement</i>		
Disagreeing & Submitting to Authority	4	1
Active (Unsanctioned) Deviation	4	1
<i>Total Job Interactions</i>	43	18
<i>Total Anomalies Uncovered</i>	15	8
Percent Resolved by Involvement	47%	78%

Table 5: Variation in Involvement

In this paper, I focus on the *consequences* of a lack of involvement as a source of resistance to rules. Below, I explore responses to anomalies in more depth and explain how involvement interacts with the familiarity of actors to produce resistance.

Responses to Anomalies at Alpha: Company Mechanics Resist the WCP Process

I first consider job interactions between operators and company mechanics at Alpha. As noted, company mechanics at Alpha are co-located with operators; mechanics are assigned to individual operating units, where they learn to work on the same equipment and with the same operators over a period of years. When actors are involved, the familiarity that mechanics develop with the equipment and with operators is conducive to effective problem solving. When involvement is lacking, however, familiarity forms the basis for coordinated resistance.

Discussion & Joint Interpretation: Familiarity as an Asset

When actors are involved, familiarity promotes effective problem solving in the form of *discussion & joint interpretation*. Such discussions may occur during a walkdown, or after work has already begun. Discussion occurs between equal parties who jointly determine the best way forward.

For example, one morning I observed a crew of mechanics working on disassembling and cleaning a series of small pipes and vessels surrounding a pump. The crew determined that to correctly proceed, the job scope would need to be expanded to include lifting out a heavy cap to further clean out an obstructed area. The mechanics called the operator, who agreed that allowing the unit to run without a more thorough cleaning would cause the same problem to recur, requiring another expensive part to be replaced. Together, they approached an operations manager who accepted their suggestion and began creating the necessary job permits to expand the job.

In this example, the expert knowledge of both parties contributed to a successful resolution. The mechanics understood the particular equipment and could sense that residue remained; in turn, the operator understood the original reason for the repair and the importance of the work for continued operation of the unit. Although the original job plan was incomplete, the mechanics were empowered to discover the problem and suggest a revision. A potential tension between the application of the process and the reality of work was resolved through the involvement of expert actors.

Submitting to Authority: Building a Narrative of Resistance

On many other occasions workers find that their involvement in the resolution anomalies through discussion is limited. On such occasions, responses instead constitute a form of resistance. In the first response, workers *submit to authority* and present a narrative of resistance. Often, that narrative is an attempt to reclaim expertise over what makes safe work. To do so, actors juxtapose unnecessary interruptions against instances where the process fails to control risk. Such claims paint a picture of a process that is ineffective and arbitrary, and that therefore cannot replace expert knowledge as a basis for safety.

For example, on one occasion I observed workers discover during a job walkdown that the wrong number was listed on a permit. The job was to use a crane to lift a broken valve from a deck fifty feet high, so that it could be moved to a shop for repair. Based on their experience in the unit, the workers knew which valve was damaged, how it should be lifted, and that the delay was likely due to a clerical error (a similar problem had occurred recently). One mechanic explained his frustration:

“Here we go again. When this happens, it’s usually hours before we can get to work. The boss will need to sign the permit again, but he just left for his 8 am meeting, and then after that he has his 9 am, so it will be hours before they find him. And usually, it’s because of a simple error. I’ll bet that the guy copied the permit from an old one but forgot to change the number.” *Company Mechanic, Alpha (paraphrased from field notes)*

Sure enough, the mechanic’s suspicion was correct. I observed as the crew spent the entire morning sitting in the shelter, all because someone forgot to change a number.

To a manager or outside observer, anomalies like incorrect numbers should be a cause for delay. The process *works* by flagging anomalies as deviant and preventing actors from normalizing them (Vaughan 1996). If actors learn that it is acceptable to

complete work even when numbers are misaligned, the risk of work being performed on the wrong equipment at a later date is increased. Such a risk is not trivial: workers can be gravely injured if work is performed on live equipment.

Workers who are familiar with the equipment, however, know very quickly when anomalies are a result of obvious errors or omissions. In such cases, the lack of flexibility introduces a gap between the requirements of the process and the goal of safety. Rather than working to fix a real problem, workers are left waiting, sometimes for hours, while their expertise is ignored.

In response, workers may attempt to reestablish their expertise by placing the event in the context of a broader narrative. In the above example, I listened as mechanics first revisited several similar incidents where errors had needlessly slowed work. A second valve was one foot away from the valve that would be lifted today. On a previous occasion, work had been delayed because a separate permit was required for that valve. Why, given identical risks, could the same permit not be used? Mechanics next juxtaposed these incidents against instances where management was not willing to wait at all. For example, a metal grate covered a fan at the other end of the deck. As we were waiting, two mechanics complained to a third who had just returned from vacation about a recent incident with this grate. Someone had cut the grate off without their knowledge, and they had been asked to tie it back on. Why hadn't they been called to remove the grate correctly? Why couldn't they now wait a few days to order a part and replace it correctly? A second issue concerned the day's work of repairing valves. Later in the day, the same crew would be asked to disconnect another valve at a location where there

was a higher than normal risk that material could escape. Why couldn't this work wait two months until the unit was shut down?

In each case, the familiarity of mechanics causes them to view disagreement in the context of a broader narrative. First, due to their knowledge of the equipment and unit operations, mechanics have opinions regarding how specific equipment should be repaired and can easily identify cases where those expectations are not met. In the above example, the mechanics understood and could observe that the fan grate was not removed and repaired correctly. Relationships with operators contribute to such knowledge: for example, the mechanics knew from discussions with operators that the unit would be shut down soon and that risky work could possibly be delayed. Second, mechanics are present to observe a pattern of incidents where work is interrupted or authority is overly limited. Hodson (2001) argues that workers have a desire for the autonomy necessary to master complex work tasks. When such autonomy is repeatedly denied, workers may well resist.

Across the plant, the narrative of resistance is crystallized among company mechanics and operators in the view that the WCP process is no more than 'lawsuit protection.' One morning, I watched a company mechanic as he filled out his portion of the work permit. After writing the usual lines "beware of slips, trips & falls" and "beware of pinch points," he said to me:

"This whole thing is about lawsuit protection. Why else would they want me to sign that I am aware of tripping hazards? That doesn't help me. That's obvious. It's all so that if something happens - if I trip - they can say 'I told you so.'"
Company mechanic, Alpha (paraphrased from field notes)

For this mechanic, the act of writing down that he should be careful not to trip is degrading. Mechanics want to be involved in managing anomalies and seeing work

performed safely and correctly. Yet, due to unanticipated problems in the implementation of the process, such efforts are too often lost.

Deviating from the Process: Active Resistance

Beyond building a narrative of resistance, workers also respond by actively *deviating* from either the letter or spirit of the process. Deviations may occur in response to individual anomalies, or be reflected in broader patterns of behavior, such as behavior on walkdowns.

First, company mechanics may deviate in response to individual anomalies. Once again, the lack of flexibility built into the process sets the stage for such behavior: when deviations appear minor, mechanics may opt to deviate rather than delay work. For example, one morning I shadowed a crew of company mechanics that was assigned to tighten bolts in a series of locations where small potential leaks had been detected. On this morning one of the locations presented a complication: the potential leak was above our heads in a location that required the use of a ladder and a small amount of climbing. The mechanics knew how to reach the bolt safely (they went to retrieve a safety harness), but were uncertain as to whether the permit allowed them to do the work. The specific task of climbing was not included in the risk assessment. However, rather than involve the operator and delay the job by requesting a separate, amended permit, they decided to deviate by moving ahead with the work.

Once again, the familiarity of the mechanics contributes to their response. In particular, mechanics are able to deviate only with the implicit consent of operators, who choose not to participate in a thorough walkdown or enforce a literal interpretation of the process. The behavior of operators, in turn, is a function of mechanics' familiarity.

Because mechanics know the location of the equipment, a thorough walkdown is not a practical necessity, as it might be if the mechanics were contractors. In addition, operators view company mechanics as peers and are not willing to look over their shoulders. As one operator put it:

“If it’s a new guy, yeah, I’ll go out there to make sure he knows what he’s doing. But for these guys who’ve been working here for years, I’m not going to go tell them to wear gloves.” – *Operator, Alpha (paraphrased from field notes)*

This operator also adopts the view that the WCP process can degrade mechanics’ knowledge. If mechanics are expert, is it necessary to tell them that they must wear gloves? Quantitative data confirms that familiarity influences behavior on walkdowns: as shown in Figure 4 (above), workers are especially unlikely to perform walkdowns when mechanics are company mechanics (10% vs. 48% for contractors).

Failure to participate in walkdowns is itself an act of deviance. Partly, behavior on walkdowns reflects a conspiracy, again made possible by personal relationships and company mechanics’ expert knowledge. Operators and mechanics know that occasionally maintenance jobs will be audited. During job audits, mechanics are asked whether a walkdown occurred, and are also asked to list what material is in nearby pipes – a question that most mechanics would not be able to answer absent a discussion with an operator. However, local company mechanics often do know what is in pipes. In addition, operators trust that company mechanics will lie and say that a walkdown occurred. Thus, the failure to perform walkdowns is an overt act of resistance.

Responses to Anomalies at Alpha: Operators Extend Resistance to Interactions with Contractors

I next consider interactions between operators at Alpha and contractor mechanics. Contractors make up a large fraction of the maintenance workforce at both plants. Although many contractors have worked at the plants for years, most contractors have far less job security than company mechanics and operators. Maintenance staffing fluctuates throughout the year, and contractors are brought into the plant as needed. Contractors also may work anywhere throughout the plant, and thus do not develop the same familiarity with equipment as company mechanics. Finally, because contractors are sometimes viewed as replacing potential union jobs, operators are less open to developing strong personal relationships with them.

These features of the contractor-operator relationship lead to different patterns of interaction in response to anomalies. On the one hand, the gap in power between operators and contractor mechanics allows operators to extend strategies of resistance into some interactions with contractors. At the same time, the lack of familiarity limits coordinated resistance.

I observed two broad patterns of interaction. First, the interaction may be characterized as one of *explaining & correcting*. Given contractors' relative lack of knowledge, operators at times have no choice but to be involved in directing work that is ongoing in the unit. For example, on one occasion an operator noticed an anomaly in a job plan. Ordinarily, work that is head high requires the construction of scaffolding; however, on this day scaffolding was not included. The operator asked the mechanics to return to their supervisor and arrange for scaffolding to be erected. Shortly after, the

operator learned from his supervisor that this job was an exception – because the mechanics would only be lifting very light objects, scaffolding was not required. However, the message was lost, and the mechanics returned several hours later with a scaffolding crew. The operator asked them why they were putting scaffolding up, to which they answered, ‘because you told us to. Isn’t that what you want?’ The mechanics simply followed the operator’s instruction, and made no effort to reason that the scaffolding was unnecessary. While company mechanics might take the initiative to make an exception or deviate independently, contractors want and depend upon the operator’s involvement. Contractors are also far less interested in resisting in the face of interruptions. One morning I observed a contractor navigate a series of problems that delayed work for several hours. I asked him if he was frustrated, to which he replied, curtly: “It doesn’t matter to me! They’re paying me by the hour. Now if they were paying us by the job, then half the people here would walk out.”

In the second pattern of interaction, operators carry strategies of resistance into interactions with contractors. For example, when an operator believes that his involvement is cut short, he may respond as above by building a narrative of resistance, even as the contractor remains mostly unmoved. For example, on one occasion an operator began to correct a contractor who he believed was using an incorrect job permit. After a discussion with another operator, however, it was revealed that the permit was correct and the job was an exceptional case. Still, the operator remained worried that a manager during an audit or incident investigation would not see it that way. “We all know that if something happens, the first thing they’re going to ask is – why weren’t you using that permit?” Out of frustration, he uses the opportunity to undermine the process.

He turns to the contractor, and says, “just so you know, this has nothing to do with you being safer. It’s all about the [expletive] permit.” The operator does not believe that he has any authority to make even a reasoned exception to a rule. As a result, he resists by attacking the legitimacy of the process.

In addition, as presented in Table 4 and described above, operators continue to deviate on walkdowns. Yet, due to contractors’ lack of familiarity, resistance to walkdowns is less complete. Particularly for high and medium risk work, operators do choose to perform walkdowns. In part, the lack of trust between operators and contractors contributes to greater compliance: operators know that they also are responsible should an audit uncover a violation, and don’t want to be hurt by a contractor’s mistake. One operator gave an example:

“Once they audited a job in Matt’s area. Now, this was an unusual job, and the contractors were required to wear these life-preserver type things. Matt told them [to wear them], but they still weren’t doing it. And then he was called out on it. Now how is that his fault? Are we supposed to babysit these guys?” *Operator, Alpha (paraphrased from field notes)*

Even as they resist the WCP process, operators at Alpha understand the hazardous nature of work and will participate in maintenance work according to their own assessment of risk. As a result, when contractors lack familiarity, resistance is muted.

Responses to Anomalies at Beta: Anomalies as a Source of Involvement

At Beta, patterns of interaction follow an entirely different course. Although actors at Beta experience many similar problems and anomalies – from errors on permits and job plans to exceptional cases - the increased involvement of actors produces different responses. Once again, however, the familiarity of actors interacts with

involvement in important ways. The lack of familiarity of mechanics at Beta further strengthens participation in the walk down rule. Actors at Beta not only comply with the walkdown rule, but also insist on performing walkdowns even when not required. Walkdowns are viewed as a crucial last line of defense against errors or unsafe conditions.

In contrast to company mechanics at Alpha, company mechanics at Beta are not co-located with operators. Company mechanics have centralized workshops that are located at the outskirts of the process units, and may be assigned to work in any of the units. Unlike at Alpha, I rarely observed company mechanics socializing with operators in operations shelters. The relative lack of familiarity means that company mechanics, like contractors, remain dependent upon operators to verify that equipment is safe and to update them on the condition of the unit and the status of work. In turn, operators develop greater authority across all interactions and view anomalies as a reason to become more involved in ensuring the safety of those working in the unit.

Operators at Beta refer directly to the concept of familiarity in explaining why they perform walkdowns:

“I [like to] go out with the craft person that day and ... push a start button on a pump to show him that ...the electrical energy is isolated. I still like to rod out a bleed and show him that the pump’s completely drained, empty. And a lot of them ask me to do it because it makes them feel comfortable... I’ve had guys say... I’m not sure which pump this is, or, I’m not sure which fan this is, you know? You actually have to walk out there with them and say this is the fan you want.” *Operator, Beta (direct quote from interview)*

According to this operator, many mechanics do not know the location of equipment and depend on operators to be sure that equipment is prepared. Mechanics want operators to press start buttons to test that they have been disconnected from power sources

("isolated"), and stick a rod into a pipe opening to ensure that the pipe is in fact empty and is not blocked ("rod out a bleed.") Mechanics with experience working in the unit could perform these tasks themselves.

Even experienced company mechanics value discussions with operators. As one company mechanic described:

"To me the safest way you can do something is for us to go out there and talk to the people that are actually running the unit. They know what they have, they know what work needs to be done." – *Company Mechanic, Beta (direct quote from interview)*

Because company mechanics are not located in the units, they do not know what repairs are needed or why they are needed, and depend on discussions with operators before work begins.

Actors support walkdowns precisely because of the opportunity to be involved in making work safer. As one company mechanic explained:

"We have a lot of links in the chain. And there's a lot of signatures on there. And you start to fall back, well, he signed it, so I think it's good. And then you sign it. And you want to hope that the guy that signed it ahead of you didn't think the same thing, well, I'll sign it because the next guy will catch it. ... I like it when we work directly with the operators, walk to the job and talk to them about the job" - *Company Mechanic, Beta (direct quote from interview)*

Operators share this sentiment, as confirmed by a story that I heard on several occasions.

On one occasion, a walkdown was performed by a manager, who opted not to climb up into the unit to point out the exact location of a piece of equipment that needed repair.

When the mechanic (a contractor) climbed up to begin work, he started to work at the wrong location – before an operator stopped him. Operators shared this story to illustrate their view that "the process doesn't make it safe, we do." When mechanics lack local knowledge, walkdowns become an essential last line of defense.

The authority that operators develop in interactions influences how both operators and mechanics interpret and respond to anomalies. Two strategies described above are especially prevalent at Beta: explaining & correcting, and discussion & joint interpretation. In addition, I describe a third strategy: looking out for others.

Explaining & Correcting

At Beta, interactions between operators and mechanics more often involve *explaining & correcting*, especially when mechanics are contractors. In each case, operators respond to anomalies by educating mechanics about the job location or safety rules, or by initiating steps to correct the error.

At times, explaining and correcting can serve to resolve disagreement and eliminate potential sources of resistance. For example, on one occasion a group of contractor mechanics was preparing to pump acid into a vessel in order to clean off residue. The operator stopped the crew and informed them that it was necessary to move the tape barricade further away from the job location, as an added precaution in case any acid spilled. The contractors originally disagreed, but the operator insisted and explained the reason for the rule.

Such interactions provide operators with opportunities to exercise authority. Although workers do at times disagree with rules, the gap in knowledge and authority between operators and mechanics leads to situations where operators can enforce rules that are not controversial. Examples include wearing hearing protection, putting barricades around work sites, wearing safety harnesses when working at heights, and ensuring that equipment is correctly de-energized. Such opportunities give meaning to job walkdowns.

Looking Out for Others

Other anomalies are not so easily resolved. Even so, operators often approach these anomalies out of an obligation to look out for and protect mechanics.

For example, on one occasion, a problem emerged while a group of operators was preparing for a job. A pipe in an unused section of the unit needed to be unbolted so that it could be washed out and capped. Usually, pipes have a small outlet with a faucet so that material can be drained in a controlled manner, and so that operators can verify that the pipe is empty. However, this pipe had a rusted cap in place of a faucet, and the group worried that if they removed the cap, they would not be able to replace it in case material started to escape. I listened as an operator and two supervisors engaged in a lengthy discussion regarding how best to proceed. As one person explained it, according to the rule, the safest way to perform the job was to have a maintenance crew begin to unbolt the two pipes. In this way, they could at least close the pipes quickly if material started to escape. However, the operator was adamant that they choose an alternate approach. As he later explained to me: "I'm the operator here, I know and understand the unit, so it's my job to take that risk and not expose them to any danger. If I'm not willing to do it, then why should they be willing to do it?"

In general, operators at Beta state that they want mechanics to feel comfortable. Once again, familiarity has a large influence on this mindset. Precisely because mechanics are coming into a hazardous environment with which they are unfamiliar, operators take seriously their responsibility to ensure that jobs are prepared safely.

Later in the day, this operator used this example to explain his frustration with the WCP process. Because the job spanned two units, managers failed to notice it on the schedule and did not complete a job plan ahead of time, leaving the operator and his supervisors to come up with a solution at the last minute. The operator was involved only by accident. “In theory the process works,” he told me, “but then problems like this happen. It was much simpler when me and the other operator could get together and make sure the job was safe.” For operators, implementation problems in the planning of maintenance work are seen as a reason to become *more* involved.

Discussion & Joint Interpretation

Finally, operators and mechanics – both contractor and company – engage in *discussion & joint interpretation*. When an anomaly emerges, workers discuss the problem, consider alternatives, and jointly choose a path forward.

Once again, the structure of the operator-mechanic interaction facilitates involvement. Because operators want mechanics to feel comfortable, they are open to their opinions when problems do not have a straightforward answer. In turn, because mechanics are unfamiliar with the unit, they are less likely to immediately dismiss anomalies and more open to discussions with operators. These discussions once again increase participation in rule systems.

For example, on one morning I observed an operator and a contractor mechanic confront an anomaly: the numbers on the job permit, on a fan that needed repair, and on the circuit breaker to shut off the fan were all different. Recall a very similar anomaly at Alpha described above. At Alpha, company mechanics immediately knew that the

misaligned number was a clerical error, and considered the error in the context of a series of decisions that undermined their authority or needlessly delayed work. At Beta, the interaction followed a different path:

After Tim (the operator) finishes his morning rounds, I follow him back to the shelter where he greets John, the maintenance mechanic who will perform the fan preventive maintenance (PM) job that morning. Tim and John head out to the unit to inspect the fan in question. Reaching this fan is a bit of a challenge; we must climb up a flight of stairs, walk along a raised walkway, and then climb a short ladder to reach the area where the fan unit is housed. There are three fan units under a low roof, each in a box about waist high and about 10 feet long by 4 feet wide. I stand aside while Tim and John have a discussion beside the middle fan. The problem that they are discussing is the fact that the number on the work order does not match the number on the fan. The two look at the paper several times, walk from one fan to the next, and try to determine whether they are looking for the numbers in the right places.

Tim is sure that the middle fan is the fan that needs work, however, and suggests that they proceed with the verification. John remains by the fan while Tim and I climb back down to the ground level. We head over to a location on the ground level where there are five or six switches attached to a pole – all have chipped paint and show the effect of years of wear. Tim flips the switch that corresponds to the middle fan, and then walks over to a place where he can see John, who is still up above on the fan deck. John signals that the fan is still off, indicating that the power supply has been effectively cut. A circuit box 20 yards away – also one in a row of five or six - has been locked in the “off” position. John meets us on the ground, and together we look at the switches. The two now check the numbers on the switches, and determine that these also do not match - either to the work order or to the fan above. We walk over to the circuit breaker, where Tim again inspects to ensure that he has locked the correct one. Tim asks John whether he is comfortable proceeding, and John tells him ‘yes’. As we are walking back, Tim explains to me that although he is a little wary that the numbers don’t match, because they have physically verified the lockout, and because the mechanic told him that he is comfortable going ahead, he will allow it.

Notice several features of this interaction. First, because the mechanic is unfamiliar with the unit, he treats the misaligned numbers as a potentially serious anomaly that requires investigation. In contrast, a mechanic who had worked in the unit for years would know from direct experience what fan needs work and where the switch and circuit breaker are located. As in the example at Alpha, misaligned numbers would interfere with his ability

to verify directly that the correct fan is locked out. In addition, although the operator does have such knowledge, he is concerned about the mechanic's comfort. If the fan is accidentally activated during work, the mechanic will be hurt, and not the operator. As a result, the two engage in a thorough discussion in which they evaluate evidence (test the switch) and choose a path forward. An anomaly that might be a source of resistance under different circumstances is instead a source of involvement.

Note, however, that such involvement comes at a cost. When actors are afforded the flexibility to manage anomalies, at times they may choose to deviate from a rule. In the above example, the actors violate the rule that numbers must be aligned, and learn (due to the absence of an event) that such deviation is acceptable. The process that they follow – evaluating evidence and reclassifying an anomaly as normal – is exactly the process that Vaughan (1996) terms the normalization of deviance. Thus, while involvement can increase the effectiveness of a system of rules through responses like explaining & correcting, when actors encounter uncertain situations, involvement does not preclude deviation. In contrast, when actors believe that they lack authority they may at times be *less* inclined to deviate – as in the case of the misaligned numbers at Alpha. Such compliance, though, comes at a cost of resistance in other forms. Managing risk remains a real challenge with complex tradeoffs.

Discussion – Resistance to Bureaucratic Rules

Worker resistance to job walkdowns at Alpha is a surprising finding. Walkdowns have clear safety benefits as acknowledged by both the practical and academic literature. Maintenance work in this industry is highly routine and well-known procedures and

controls exist to reduce the risk of accidents. Moreover, workers at both Beta and Alpha are intimately aware of the risks of work, and do not fear retaliation or time pressures. Workers also routinely encounter anomalies during work and understand the benefits of the practice. Plant management, for its part, has invested substantial resources in the larger WCP process, and is also under considerable pressure to see safety outcomes improve.

I argue that the divergence between Beta and Alpha is explained by the interaction between two factors: the involvement and the familiarity of the front line workforce. As we might expect in all rule systems, front line actors often encounter gaps between rules and the demands of work (Brown & Duguid 1991, Orr 1996). Such anomalies are especially likely in a strict control system like the WCP process that deliberately reduces the flexibility of front line actors so as to reduce operational risk. At Alpha, because company mechanics are co-located, interruptions caused by an inflexible process are more likely to be viewed as threatening to expert knowledge. Actors believe that their expertise is not valued, and respond by resisting practices like the job walkdown. Due to personal relationships between company mechanics and operators, workers share stories and jointly develop strategies of resistance that extend to interactions between operators and contractors.

In contrast, when operators and mechanics are not co-located, mechanics lack familiarity with the unit and remain reliant upon walkdowns. Even when involvement is low, walkdowns often remain necessary and resistance is less possible. When involvement is high, the lack of familiarity provides even greater motivation for engagement. Operators use their authority to participate in managing anomalies by

enforcing rules, suggesting resolutions, and raising issues with managers as appropriate.

Table 6 summarizes the differences observed across interactions.

Type of Interaction	Alpha (Company Mechanics are Co-located)	Beta (Company Mechanics are not Co-located)
Operators and Company Mechanics	<ul style="list-style-type: none"> - Mechanics experience threats to dignity due to conflicts between local knowledge, inflexible process - Mechanics & operators establish narrative of WCP process as ‘lawsuit protection’ - Mechanics conspire with operators to advance narrative, avoid walkdowns <p><u>Common Responses to Anomalies</u></p> <ul style="list-style-type: none"> - Discussion & Joint Interpretation - Building a Narrative of Resistance - Active Deviation 	<ul style="list-style-type: none"> - Mechanics experience (weaker) threats to dignity due to inflexible process - Walkdowns remain necessary due to lack of knowledge of unit conditions - Mechanics isolated from operators, can’t initiate resistance <p><u>Common Responses to Anomalies</u></p> <ul style="list-style-type: none"> - Looking Out for Others - Discussion & Joint Interpretation
Operators and Contractor Mechanics	<ul style="list-style-type: none"> - Mechanics seek operator involvement but have limited power in interaction - Operators advance ‘lawsuit protection’ narrative based on perception that knowledge is not valued - Operators perform walkdowns based on individual assessment of risk (only for medium & high risk work) <p><u>Common Responses to Anomalies</u></p> <ul style="list-style-type: none"> - Explaining & Correcting - Building a Narrative of Resistance - Active Deviation 	<ul style="list-style-type: none"> - Mechanics seek operator involvement - Process errors are less threatening to operators; operators instead see errors as a reason to become more involved - Operators want mechanics to feel ‘comfortable’ <p><u>Common Responses to Anomalies</u></p> <ul style="list-style-type: none"> - Explaining & Correcting - Looking Out for Others - Discussion & Joint Interpretation

Table 6: Responses to the WCP Process at Alpha & Beta, by Type of Interaction

Drawbacks of Familiarity

The finding that familiarity can decrease compliance with rules has important implications for organization theory. Generally, familiarity is viewed as contributing to positive organizational outcomes. Numerous studies have shown that familiarity leads to

increased performance (Harrison et al. 2003; Reagans, Argote & Brooks 2005; Espinosa et al. 2007; Huckman, Staats & Upton 2009). Organizations, groups and individuals learn through cumulative experience (Argote, Beckman & Epple 1990), and teams improve their ability to coordinate on complex tasks as individuals gain experience working with one another (Huckman, Staats & Upton 2009). More broadly, actors gain valuable knowledge by collaborating to form communities of practice (Brown & Duguid 1991), and by forming strong ties based on trust (Uzzi 1997; McEvily, Perrone & Zaheer 2003). Finally, in the context of safety & reliability, familiarity increases psychological safety, causing workers to report errors more frequently and allowing organizations to learn from those errors (Edmondson 1999). Familiarity is also essential to the development of the “collective mind” necessary to achieve reliability in complex operations (Weick & Roberts 1993).

The positive effects of familiarity are clear in the interactions between operators and mechanics. At Alpha, where company mechanics and operators are co-located, company mechanics notice problems that others might not and are comfortable raising those problems with operators and with managers. Operators and expert mechanics engage in discussion and joint interpretation that benefits from shared knowledge. In contrast, when mechanics lack power in the interaction, they are dependent upon operators to show interest in their safety. Company mechanics (and some contractors) at both plants also benefit from the years of cumulative experience performing maintenance tasks.

At the same time, the above results indicate that familiarity can have a downside. Precisely because workers develop familiarity with a task and with one another, they are

more likely to resist standard practices and better able to coordinate to resist those practices. Through past interactions, actors assess risk and normalize some anomalies (Vaughan 1996). Such normalization is essential to coordinated action: cognitive processes naturally work to categorize anomalies as examples of known phenomena (Silbey 2009). Thus, when control systems continually create anomalies yet fail to allow actors some flexibility to manage those anomalies, local assessments of risk will likely come into conflict with rules. At times, such conflict is beneficial: by remaining inflexible, control systems preserve boundaries between normal and deviant and prevent accidents. However, given that control systems are always incomplete, at other times inflexibility may appear unwarranted and may become a source of resistance. Actors may resist even those rules that contribute to their own safety.

In contrast, when actors are unfamiliar, anomalies are new events. Although actors may still choose to normalize anomalies that are deviant, the occurrence of an anomaly is not itself a threat to existing knowledge. Actors are compelled to perform full evaluations of anomalies and may discover problems that otherwise would not be raised. In addition, actors are more likely to adopt standard practices that reduce risk.

Familiarity, then, has a more complex influence than typically acknowledged. At times, familiarity increases actors' ability to recognize, report, and prevent problems. At other times, organizations benefit when anomalies are treated as new events. Can organizations possibly achieve the advantages of both?

Familiarity and Employee Involvement

To start, the experience at Alpha suggests that organizations may require a different approach to rules in order to reap the benefits of familiarity. Given that no rule system can possibly address all contingencies, when actors are familiar, organizations must allow expert actors increased involvement in managing anomalies that do arise. At Alpha, such involvement is lacking.

The tension between standardization and employee involvement is not a new theme in organization theory. In particular, such tension is a major theme in research on the adoption of participative management, total quality management, and other practices during the 1990s (e.g. Lawler 1994). Vallas (2003) argues that the conflict between the logic of standardization and the logic of participation is a major reason why such efforts so often failed. Yet, while management scholars have long noted the importance of involvement, very often involvement is conflated with the effects of rule *content*. That is, in situations where lack of involvement is theorized to explain resistance to standard rules, rules are also not in workers' interests. Employees may resist standard practices that threaten their autonomy, or resist practices that threaten to put them out of a job as a result of overall productivity gains (Repenning 2000). In my case, however, the goal of rules is to *advance* worker interests: the WCP process is designed to reduce risk and improve workplace safety, at the expense of productivity. Yet, even when the goal of rules is favorable to workers, standardization and involvement once again come into conflict.

The results here suggest that eventually there is a limit to the regulation of risk, quality, or any other organizational outcome. The more fine-grained rules become, the

more likely rules are to run up against anomalies that appear to contradict their very purpose. In the face of anomalies, expert actors will inevitably face situations in which accepting or normalizing deviance appears logical or even necessary. In such cases, either rules become decoupled from work (Meyer & Rowan 1977), or become the basis for ongoing conflict and resistance.

Instead, organizations might accept the limits of rules and allow greater interpretive flexibility within boundaries that can be justified and easily maintained. Vaughan (2005a) describes such an arrangement as it occurs in US air traffic control. Operators are highly trained and use experiential knowledge to navigate many situations, yet deviations from normal are quickly identified. Similarly, Huising & Silbey (2011) suggest that organizations strive not to be perfectly compliant, but instead “close to compliant.” Organizations should identify rules that can be consistently enforced and establish channels where front line actors can be involved in managing anomalies. The power and knowledge difference between operators and mechanics at Beta provides one source of involvement; where actors are more familiar, organizations must establish additional channels.

Limitations and Future Research

The results here have several limitations and suggest several possible avenues for future research. First, it is important to distinguish between the outcome of compliance and other outcomes including safety and work quality. Although lower familiarity leads to greater compliance with the walkdown practice, such a result does not necessarily imply improved safety: the positive effects of familiarity may still outweigh any negative

effects of weaker compliance. On the other hand, when resistance influences even those interactions where actors are not familiar – such as operator-contractor interactions at Alpha, safety almost certainly suffers.

Future research might explore the conditions under which familiarity is more or less important in work interactions. For more complex tasks, the value of familiarity is well established. For simpler, repetitive tasks, would performance improve if individuals lacked familiarity? Alternatively, are there other methods to inject novelty into organizational life to overcome some of the drawbacks of familiarity? Too often, challenges to existing routines and patterns of thought come only in the form of accidents. Could organizations structure interactions to include a mix of familiar and unfamiliar actors in order to benefit from both perspectives? As the experience at Beta suggests, brief interactions like job walkdowns can be highly effective when implemented in the right context. Likewise, Silbey (2009) suggests that organizations should seek to challenge the processes of normalization.

A second limitation concerns additional actions that managers might take to limit anomalies or promote involvement when anomalies do occur. Although the two sites here are matched on a wide variety of factors, individual line managers may pursue strategies that are more or less effective, even while implementing an identical process. For example, managers might take additional steps to encourage participation and validate workers' concerns. Variations in equipment reliability, staffing, and experience may also influence the frequency of anomalies. Such variation exists between process units at both plants, but is not sufficient to influence the overall behavior described above.

Finally, future research might consider the evolution of systems of rules over time. Although I asked actors to describe the timeline of events in interviews, the analysis here is mainly cross-sectional. Given the tension that exists between both plants over the new process, additional research might ask how that tension will be resolved over time. Will management emphasis on the process eventually give way, leading to decoupling between rules and work practice (Meyer & Rowan 1978)? Are there alternatives to such an outcome? For example, if organizations allow some interpretive flexibility within rules that are more easily enforced, is compliance improved in the long run? These questions provide several possibilities for further investigation.

References

- Adler, P. S., & Borys, B. 1996. Two Types of Bureaucracy: Enabling and Coercive. *Administrative Science Quarterly*, 41(1): 61-89.
- Argote, L., Beckman, S. L., & Epple, D. 1990. The Persistence and Transfer of Learning in Industrial Settings. *Management Science*, 36(2): 140–154.
- Baumard, P., & Starbuck, W. H. 2005. Learning from Failures: Why it May not Happen. *Long Range Planning*, 38(3): 281–298.
- Braverman, H. 1974. *Labor and Monopoly Capital: The Degradation of Work in the 20th Century*, New York: Monthly Review Press.
- Brown, J. S., & Duguid, P. 1991. Organizational Learning and Communities-of-Practice: Toward a Unified View of Working, Learning, and Innovation. *Organization Science*, 2(1): 40-57.
- Burawoy, M. 1982. *Manufacturing Consent: Changes in the Labor Process under Monopoly Capitalism*, Chicago: University Of Chicago Press.
- Canales, R. 2011. Rule bending, sociological citizenship, and organizational contestation in microfinance. *Regulation & Governance*, 5(1): 90-117.
- Carlile, P. R. 2002. A pragmatic view of knowledge and boundaries: boundary objects in new product development. *Organization Science*, 13(4): 442–455.
- Coglianesi, C., & Nash, J. 2001. *Regulating from the Inside: can Environmental Management Systems achieve Policy Goals?*, Washington, DC: Resources for the Future.
- Edelman, L. B. 1992. Legal ambiguity and symbolic structures: Organizational mediation of civil rights law. *The American Journal of Sociology*, 97(6): 1531–1576.
- Edelman, L. B., Erlanger, H. S., & Lande, J. 1993. Internal dispute resolution: The transformation of civil rights in the workplace. *Law & Society Review*, 27: 497.
- Edmondson, A. 1999. Psychological Safety and Learning Behavior in Work Teams. *Administrative Science Quarterly*, 44(2): 350–383.
- Edmondson, A. C., & Tucker, A. L. 2003. Why Hospitals Don't Learn from Failures: Organizational and Psychological Dynamics that Inhibit System Change. *California Management Review*, 45(2): 55–72.
- Eldridge, J. E. T. 1968. *Industrial disputes: Essays in the Sociology of Industrial Relations*, London: Routledge & K. Paul.

- Espinosa, J. A., Slaughter, S. A., Kraut, R. E., & Herbsleb, J. D. 2007. Familiarity, complexity, and team performance in geographically distributed software development. *Organization Science*, 18(4): 613–630.
- Freeland, R. F. 2001. *The Struggle for Control of the Modern Corporation: Organizational Change at General Motors, 1924-1970*, Cambridge: Cambridge University Press.
- Glaser, B. G., & Strauss, A. L. 1967. *The Discovery of Grounded Theory: Strategies for Qualitative Research*, New Brunswick, NJ: Aldine Transaction.
- Granovetter, M. 1985. Economic Action and Social Structure: The Problem of Embeddedness. *American Journal of Sociology*, 91(3): 481–510.
- Hall, A. 1993. The Corporate Construction of Occupational Health and Safety: A Labour Process Analysis. *The Canadian Journal of Sociology*, 18(1): 1–20.
- Harrison, D. A., Mohammed, S., McGrath, J. E., Florey, A. T., & Vanderstoep, S. W. 2003. Time matters in team performance: Effects of member familiarity, entrainment, and task discontinuity on speed and quality. *Personnel Psychology*, 56(3): 633–669.
- Haynes, A. B., Weiser, T. G., Berry, W. R., Lipsitz, S. R., Breizat, A. H. S., Dellinger, E. P., et al. 2009. A surgical safety checklist to reduce morbidity and mortality in a global population. *New England Journal of Medicine*, 360(5): 491–499.
- Heimer CA. 1992 Doing Your Job and Helping Your Friends: Universalistic Norms about Obligations to Particular Others in Networks. In Nohria N and Eccles R G. (Eds.) *Networks and Organizations: Structure, Form, and Action*, pp. 143–164. Boston, MA: Harvard Business School Press.
- Hodson, R. 2001. *Dignity at Work*, Cambridge: Cambridge University Press.
- Huckman, R. S., Staats, B. R., & Upton, D. M. 2009. Team Familiarity, Role Experience, and Performance: Evidence from Indian Software Services. *Management Science*, 55(1): 85–100.
- Huising, R., & Silbey, S. S. 2011. Governing the gap: Forging safe science through relational regulation. *Regulation & Governance*, 5(1): 14–42.
- Katz, D. 1964. The motivational basis of organizational behavior. *Behavioral Science*, 9(2): 131–146.
- Kellogg, K. C. 2009. Operating room: relational spaces and microinstitutional change in surgery. *American Journal of Sociology*, 115(3): 657.

- Kelly, E. L., & Dobbin, F. 2007. How to stop harassment: Professional construction of legal compliance in organizations. *American Journal of Sociology*, 112(4): 1203–1243.
- Lawler III, E. E. 1994. Total quality management and employee involvement: are they compatible? *The Academy of Management Executive (1993-2005)*, 68–76.
- Lipsky, M. 1980. *Street-Level Bureaucracy: Dilemmas of the Individual in Public Service*, New York: Russell Sage Foundation Publications.
- Meyer, J. W., & Rowan, B. 1977. Institutionalized organizations: Formal structure as myth and ceremony. *The American Journal of Sociology*, 83(2): 340–363.
- Morrill, C., Zald, M. N., & Rao, H. 2003. Covert Political Conflict in Organizations: Challenges from Below. *Annual Review of Sociology*, 29: 391–415.
- Morrison, E. W. 2006. Doing the job well: An investigation of pro-social rule breaking. *Journal of Management*, 32(1): 5.
- Morrison, E. W., & Milliken, F. J. 2003. Speaking up, remaining silent: The dynamics of voice and silence in organizations. *Journal of Management Studies*, 40(6): 1353–1358.
- Orr, J. E. 1996. *Talking about Machines: An Ethnography of a Modern Job*, Ithica, NY: Cornell University Press.
- Perin, C. 2005. *Shouldering Risks: The Culture of Control in the Nuclear Power Industry*, Princeton, NJ: Princeton University Press.
- Perrow, C. 1983. The organizational context of human factors engineering. *Administrative Science Quarterly*, 28(4): 521–541.
- Perrow, C. 1999. *Normal Accidents: Living with High-risk Technologies*, Princeton, NJ: Princeton University Press.
- Power, M. 1997. *The Audit Society: Rituals of Verification*, Oxford: Oxford University Press.
- Reagans, R., Argote, L., & Brooks, D. 2005. Individual experience and experience working together: Predicting learning rates from knowing who knows what and knowing how to work together. *Management Science*, 51(6): 869–881.
- Rees, J. V. 1988. *Reforming the Workplace: A Study of Self-regulation in Occupational Safety*, Philadelphia: University of Pennsylvania Press.
- Reid, D. 1981. The role of mine safety in the development of working-class consciousness and organization: The case of the Aubin Coal Basin, 1867-1914. *French Historical Studies*, 12(1): 98–119.

- Repenning, N. P. 2000. Drive out fear (unless you can drive it in): The role of agency and job security in process improvement. *Management Science*, 46(11): 1385–1396.
- Scott, W. R. 2003. *Organizations: Rational, Natural, and Open Systems*, Englewood Cliffs, NJ: Prentice Hall.
- Short, J. L., & Toffel, M. W. 2010. Making self-regulation more than merely symbolic: The critical role of the legal environment. *Administrative Science Quarterly*, 55(3): 361–369.
- Silbey, S. S. 2009. Taming Prometheus: Talk about Safety and Culture. *Annual Review of Sociology*, 35(1).
- Spear, S. J. 2009. *Chasing the Rabbit: How Market Leaders Outdistance the Competition and How Great Companies Can Catch Up and Win*, McGraw-Hill Professional.
- Star, S. L., & Griesemer, J. R. 1989. Institutional ecology, 'translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science*, 19(3): 387–420.
- Star, Susan Leigh, & Gerson, E. M. 1987. The Management and Dynamics of Anomalies in Scientific Work. *The Sociological Quarterly*, 28(2): 147-169.
- Starbuck, W. H. 2009. Cognitive reactions to rare events: Perceptions, uncertainty, and learning. *Organization Science*, 20(5): 925–937.
- Tucker, A. L., & Edmondson, A. C. 2003. Why hospitals don't learn from failures: Organizational and psychological dynamics that inhibit system change. *California Management Review*, 45(2): 55–72.
- Tyler, T. R., & Lind, E. A. 1992. A relational model of authority in groups. *Advances in Experimental Social Psychology*, 25: 115–191.
- Uzzi, B. 1997. Social Structure and Competition in Interfirm Networks: The Paradox of Embeddedness. *Administrative Science Quarterly*, 42(1): 35–67.
- Vallas, S. P. 2003. Why teamwork fails: Obstacles to workplace change in four manufacturing plants. *American Sociological Review*, 68(2): 223–250.
- Vaughan, D. 1996. *The Challenger Launch Decision: Risky technology, Culture, and Deviance at NASA*, Chicago, IL: University of Chicago Press.
- Vaughan, D. 1999. The dark side of organizations: Mistake, misconduct, and disaster. *Annual Review of Sociology*, 25(1): 271–305.
- Vaughan, D. 2005a. Organizational rituals of risk and error. In B. Hutter & M. K. Power (Eds.), *Organizational Encounters with Risk*: 33–66, Cambridge, UK: Cambridge University Press.

- Vaughan, D. 2005b. System Effects: On Slippery Slopes, Repeating Negative Patterns, and Learning from Mistake? In Starbuck, W.H. & Farjoun, M (Eds.), *Organization at the Limit: Lessons from the Columbia Disaster*: 41, Wiley-Blackwell.
- Weick, K. E., & Roberts, K. H. 1993. Collective mind in organizations: Heedful interrelating on flight decks. *Administrative Science Quarterly*, 38(3): 357–381.
- Weick, K. E., Sutcliffe, K. M., & Obstfeld, D. 1999. ‘Organizing for High Reliability: Processes of Collective Mindfulness. In R. S. Sutton & B. M. Staw (Eds.), *Research in Organizational Behavior*: 81-123, Stanford: Jai Press.
- Zaheer, A., McEvily, B., & Perrone, V. 1998. Does trust matter? Exploring the effects of interorganizational and interpersonal trust on performance. *Organization Science*, 9(2): 141–159.

Essay 2 - Overcoming the Iron Cage: The Dynamics of Rule Systems in Organizations

Abstract

The phenomenon of decoupling between formal organization and work practice has been a central theme in organization studies for decades. How do we account for the prevalence of formal structure if it is so often ineffective? Existing theories of decoupling emphasize the inherent conflict that formal structure produces, between external legitimacy and efficiency on the one hand, and between worker consent and management control on the other. Yet, such theories fail to fully explain how formal structure is occasionally highly *effective* as a means of achieving reliable outcomes. Based on a comparative ethnography of the implementation of a safety management system in two industrial plants, I develop a dynamic theory of the success and failure of rule systems in organizations. Consistent with literature in the institutional tradition, I find that pressure to conform to externally imposed norms of bureaucratic rationality is an important source of decoupling. However, rather than compelling organizations to adopt practices that are inefficient or opposed to the interests of managers or workers, external pressure creates a conflict that is *temporal*: necessary efforts to demonstrate compliance in the short run directly undermine efforts to make rules effective in the longer term. When organizational actors have the flexibility to build organizational capabilities absent imperatives to demonstrate strict compliance at all times, formal structure can evolve to become a highly effective means of organizing. Absent such flexibility, rules can become a source of conflict characterized by worker resistance, tighter control, and decoupling. These results have important implications for modern efforts to manage risk in areas such as quality, safety, and environmental performance through governance systems based on transparency, accountability and standard rules.

Introduction

Organizational theorists have long noted that work activities in organizations very often do not match the rules, procedures, and formal structures that are central to bureaucratic and other forms of organizing. The phenomenon of decoupling between rules and practice is a central theme of diverse streams of literature, from classic studies of bureaucracy (Gouldner 1954, Perrow 1984, Weick 1976), to neo-institutional theory (Meyer & Rowan 1977), to ethnographic studies of work and occupations (Orr 1996). Across these various traditions, scholars have puzzled over the apparent contradiction between bureaucratic rules that are often ineffective, and organizations' insistence on implementing and maintaining them. Why is the gap between rules and practice so enduring?

Existing explanations of decoupling in organizations emphasize the inherent tension between external imperatives and the demands of actual work practice. In particular, while organizations must subscribe to institutionalized rules and formal structures in order to establish external legitimacy, very often the same rules and structures conflict with the demands of particular circumstances (Meyer & Rowan 1977, Lipsky 1980). Such conflict can produce decoupling in at least two ways. First, managers may deliberately encourage ceremonial compliance by making goals ambiguous and failing to establish enforcement mechanisms (Meyer & Rowan 1977, Edelman 1992). Second, decoupling may develop gradually over time as rules give way to profit or production pressures (Vaughan 1996, Beamish 2000), or due to resistance from front line workers or professional or status groups (Kellogg 2009).

While the conflicts that underlie many instances of decoupling are well documented, theories that emphasize contradictions between external imperatives and internal demands increasingly fail to describe a range of cases in which the goals of institutionalized rules or regulatory requirements are *supported* by both managers and workers, and where rules are occasionally highly effective at improving outcomes. Consider the case of workplace safety - often one of the most developed areas of bureaucracy. Although organizational actors do neglect safety rules due to profit or other pressures, in other cases - especially following a major adverse event or when under pressure from regulators - efforts to implement effective safety rules are sincere. For example, Rees (1996) describes how threats to the very existence of the US nuclear power industry in the wake of the Three Mile Island accident motivated substantial changes in industry safety practices, with considerable effect. When these efforts fail to improve outcomes, failure cannot easily be dismissed as a deliberate choice of management. Nor can failure always be attributed to inherent opposition from front line workers or status groups: in industrial settings, improved safety has been a major focus of labor unions for decades (e.g. Reid 1981, Rees 1988). As Gouldner (1954) argued long ago, safety rules can be a source of *agreement* between management and the workforce, and a prime example of what he termed “representative bureaucracy.”

External imperatives may align with internal work demands in areas beyond workplace safety. In recent years, organizations have increasingly adopted audit and management systems in areas such as environmental management, financial accounting, and safety (Power 1997, Huising & Silbey 2010). Although often adopted in response to institutional or regulatory pressure, when implemented effectively, these rule-based

systems can also benefit employees, shareholders, and broader communities by decreasing the risk of serious adverse events (Coglianese & Nash 2002, Gunningham et al. 2002). In addition, the quality movement in business was built on the idea that standard rules can enhance reliability, learning, and front line engagement (Hackman & Wageman 1995, Adler & Borys 1996, Zbaracki 1998). Yet, despite the promise of these rule systems to enhance legitimacy, serve management objectives, and improve conditions for workers, very often such promise is not realized. Common objectives give way to conflict, implementation stalls, or workers resist even those rules that are in their interest. If decoupling is neither deliberate nor in the interests of workers, how else do we explain the persistence of the gap between rules and practice?

In this paper, I draw on a comparative case study of the implementation of safety rules in two industrial plants to develop a theory of the success and failure of rule systems in organizations. Consistent with existing theory, I find that external pressure to adopt rules is an important source of conflict between rules and practice. However, the mechanism by which such pressures operate differs in important ways from previous accounts. Rather than compelling organizations to pursue goals that either managers or workers oppose, external pressure creates a conflict that is *temporal*: necessary efforts to demonstrate compliance in the short run directly undermine efforts to make rules effective in the longer term.

At one plant, because managers have greater leeway to develop underlying capabilities prior to the introduction of a rule system, standard rules work as intended. Rules serve to highlight deviance and spur corrective action, thereby setting in motion reinforcing dynamics in which the participation of front line workers continually supports

effective rules. In contrast, at the second plant, stronger external pressure to demonstrate compliance immediately undercuts the implementation of an identical rule system, leading to a vicious circle of worker resistance, tighter control, and decoupling. Unfortunately, the worst performing organizations are likely to experience the greatest degree of pressure while also having the *least* ability to manage that pressure, creating a dilemma for managers and regulators and creating the conditions for persistent decoupling.

Theory: Decoupling and the Bureaucratic Form of Organization

The phenomenon of decoupling between rules and practice has been a major theme in organizational research for decades. For years, scholars have struggled to reconcile a central tension posed by the prevalence of the bureaucratic form of organization. On the one hand, the bureaucratic form has many appealing features, as first articulated by Weber. In theory, bureaucracy provides a means to coordinate a complex division of labor, thereby making possible the production of many modern goods and services in a reliable and efficient manner (Perrow 1986). Yet, despite the ubiquity and appeal of the bureaucratic form, in practice most organizations deviate in substantial ways from the bureaucratic ideal type. Why do organizations embrace bureaucracy if it so often fails to describe actual work practice? Alternatively, if bureaucracy is effective, why is work so often decoupled from formal structures and rules?

Organizational theory provides several broad answers to these questions. First, the gap between rules and practice is very often attributed to the essential tension between control and consent. While a system of formal rules and relationships may be

efficient in theory, organizations also depend on the full “consent” of individuals to act on behalf of the organization even when their effort cannot be monitored and governed by rules (Katz 1964). Selznick (1948) points out that the goals of bureaucratic control and consent are inevitably at odds: to win consent, organizations must give autonomy to those with specialized knowledge, undermining hierarchical control (Freeland 2001). Other scholars of work and organizations have emphasized the inherent conflict between management and workers in large bureaucratic organizations, and the extent to which managers must rely on informal norms to generate consent (e.g. Burawoy 1979). Thus, decoupling emerges either as actors resist control or as managers struggle to balance competing goals of efficiency and consent.

Certainly, universal rules can and do serve as instruments of control and alienation in organizations, and may become a source of resistance (e.g. Morrill, Zald & Rao 2003). Yet, the image of the iron cage is also at times problematic. Although universal rules can undermine consent, they need not necessarily do so. Gouldner (1954) describes how bureaucratic rule in some domains can be “representative”; more recently, Adler & Borys (1996) argues that rules can be enabling as well as coercive. Rules can benefit workers by providing a store of knowledge that facilitates communication and enhances involvement, cooperation, and specialization (Adler 2012). Indeed, a central promise of various workplace initiatives that appeared in the 1980s and 1990s - from quality circles, TQM, and “continuous improvement” to “participative management” more generally - was to overcome some of the limits of purely centralized control through exactly such an approach to rules (Adler 1992; Hackman & Wageman 1995; Vallas 2003). The famed Toyota Production System emphasizes that standard work

practices must be supported and continually revised through the efforts of front line workers to find and resolve defects (Spear & Bowen 1999). Critics point out that efforts to install participative systems have been largely unsuccessful, and have often simply replaced one form of alienation with another (Kunda 1992). Yet, even if success is rare, instances where bureaucratic rules and worker consent and involvement go hand and hand do exist. For example, in a study of the implementation of continuous improvement initiatives in several paper plants, Vallas (2003) finds one exceptional case where worker participation is extensive. These examples suggest that the gap between rules and practice cannot always be explained as an inherent consequence of the iron cage. Part of bureaucracy's appeal is that it is occasionally highly effective. How do we account for such effectiveness? What triggers conflict if not the design of the bureaucratic form itself?

The second explanation for decoupling is provided by neo-institutional theory, as originally articulated by Meyer & Rowan (1977). Meyer & Rowan (1977) propose a compelling solution to the problem of bureaucracy's only occasional effectiveness. Specifically, they distinguish between two types of organizations: production organizations that operate stable technologies and face strong output controls, and "institutionalized organizations" where measurement of output is more difficult (Scott & Meyer 1983). While formal structure is effective only in the former case, all organizations face an external imperative to conform to norms of rationality that emphasize reliability and accountability (Hannan & Freeman 1984). Thus, we should expect decoupling to be most pronounced in institutionalized organizations, like hospitals and schools, where the demand for external legitimacy is most salient and where the

limits of formal structures are most apparent. In such cases - and to a certain extent, in general - managers may adopt formal structure to establish external legitimacy even as they acknowledge the limits of such structure by deliberately decoupling rules from practice.

Explanations of decoupling based on the conflict between external and internal imperatives have proven to be highly persuasive. For example, a long stream of literature in the institutional tradition examines the influence on organizations of normative requirements in areas such as employment law, health and safety law, and other laws designed help disadvantaged groups (e.g. Edelman 1992; Edelman, Erlanger & Lande 1993; Kalev, Dobbin & Kelly 2006; Dobbin 2009). This literature highlights the many ways in which organizations may co-opt, redefine, or subvert requirements that conflict with the basic need to deliver products or services efficiently. External imperatives can also contribute to pressures that undermine consent: for example, in his theory of “street-level bureaucrats,” Lipsky (1980) argues that managers’ needs to uphold bureaucratic ideals of consistency and fairness often come into conflict with workers’ needs to serve diverse clients with limited resources.

Like arguments built on the problem of consent, however, the institutional approach is also only partly satisfactory. Once again, institutional accounts are weakest in settings where we might expect formal structure and universal rules to be *effective* and in support of an organization’s goals. Because the institutional explanation of decoupling takes as a starting point that norms of rationality conflict with the internal demands of organizations, it cannot explain the failure of rule systems in instances where such demands are not necessarily in conflict. Interestingly, Meyer & Rowan (1977)

acknowledge this limitation in their theory by distinguishing between types of organization. Yet, their distinction is for the most part lost in subsequent analyses (Hallett 2010), and is in either case highly problematic. Empirically, the prevalence of failures and accidents even in highly regulated, technologically mature organizations with strong output controls suggests that such organizations are not immune from decoupling. In addition, even those organizations that Meyer & Rowan (1977) describe as highly institutionalized can benefit from the positive features of formal structure. For example, in recent years both hospitals and schools in the United States have made substantial efforts to measure and standardize work outputs, by adopting practices from the quality movement in the former case and through efforts like the No Child Left Behind law in the latter. As in other organizational contexts, such efforts are occasionally highly successful and at other times not. Why do external imperatives become a source of decoupling in some cases but not in others?

A third prominent stream of literature explains the gap between rules and practice as a consequence of inherent limits in organizational design and in the rationality of organizational actors. In contrast to the first view, where the dysfunctions of bureaucracy are a result of power and control, authors in this third tradition instead emphasize information processing and cognition. Most notably, Vaughan (1996) provides a theory to explain how deviance from rules is gradually normalized, producing a gap between written rules and practice. Vaughan argues that the normalization of deviance is a result of the division of labor in large organizations. Because work groups must simplify the nuances and context of work when communicating up hierarchies or across organizational boundaries, when organizations make decisions, crucial details are at times

lost. Decisions to deviate that fail to produce negative results immediately are thus reinforced over time, causing deviations to be reclassified as normal. Vaughan's theory is consistent with much organizational research that emphasizes the nuance and complexity of local work practices in organizations (e.g. Orr 1996), the limits of cross-boundary communication (e.g. Carlisle 2002, Bechky 2003) and the bounded rationality of organizational decision-making processes (March & Simon 1958, March et al. 2000). These features of organizations are important reasons why practices can evolve to become decoupled from written rules.

The information processing view of organizations is far more successful at explaining instances of successful coordination. At certain times or in specific areas, rules and practice may be highly coupled; they are just not likely to remain so widely or over long periods of time (Snook 2002). Rule systems are likely to be most successful in producing reliable coordinated action in contexts where deviance is monitored, where rules are consistently enforced, and where structures for sharing and acting on information are well-developed (Vaughan 2005). Yet, a major weakness of this approach is that because the theory depends upon organizational blindness or ignorance, it is less able to account for instances where rules are actively contested. In contrast, institutional accounts explicitly recognize the conflict that managers face between external and internal demands, while theories of consent emphasize hierarchical conflict and power. At times, the imperative to conform to bureaucratic structures is widely acknowledged inside organizations and enforced by regulators. How do we explain variance in the success of rule systems in such cases?

The problems raised by these various approaches suggest a need to extend existing theory. Specifically, existing theory fails to provide an explanation for decoupling that accounts for the promise of formal structure, yet also explains how such structure can so often become a source of conflict and resistance. For explanations that take conflict as an inherent feature of bureaucracy, effective rule-based coordination is merely pathological. Likewise, literature in management on high performing organizations (e.g. Weick et al. 1999) fails to consider why effective coordination is so difficult to establish and why and how it is so often undermined (Silbey 2009). To overcome these limitations, I argue that a successful theory of decoupling must be *dynamic* in nature: that is, rather than assume that decoupling follows necessarily from inherent tensions in the bureaucratic form or can be described at a point in time, we must instead explicitly describe those processes by which rules come into conflict with work, how those processes create lasting resistance, and how those processes are sometimes halted. Vaughan's theory of the normalization of deviance lays the groundwork for such an approach; in this paper, I build on her argument by considering active resistance created both by the external environment and by hierarchical control.

To do so, I draw on a growing stream of literature that describes the process of creating successful compliance with rules on the front lines of organizations (Silbey 2010). Not surprisingly, such accounts reveal that compliance requires time, effort, and initiative by front line actors who are able to identify novel opportunities to improve compliance and advocate across existing organizational boundaries to promote those changes (Edmondson & Tucker 2003, Huising & Silbey 2011, Pires 2011). The effort and delay required to construct effective compliance, in turn, creates a dilemma for

organizations that must demonstrate reliable and accountable operations to senior leadership, regulators, and to the broader public in the short run. In the short run, strict rules and oversight are the least costly means to affect some improvement in the consistency of operations while also creating an image of compliance. Yet, insistence on immediate conformity directly undermines efforts to build effective coordination through the same rules in the longer term. Such tensions create an example of what Repenning & Sterman (2002) term a “capability trap”: a dynamic in which an increasing short-term focus is self-reinforcing. To improve performance, organizations must accept some degree of worse performance in the short run. I argue that the effect of external imperatives is not always to compel organizations to create rules and structures that are opposed to their interests, but rather to compel organizations to adopt structures in such a way that undermines their ultimate effectiveness. For organizations that have made long term investments to build compliance, external imperatives can be helpful; for most, however - including those that fall behind competitors on some level of performance - the opposite is true. Thus, bureaucratic structures have occasional and real promise and at the same time produce conflict and resistance.

The remainder of the paper is organized as follows. I first explain the research sites and methods. Next, I provide a case narrative of efforts to implement the same bureaucratic rules in two highly similar industrial plants. Third, I build on existing theory to develop a dynamic model of the implementation of bureaucratic rules, and use that model to explain contrasting outcomes between the two sites. I conclude by drawing several general lessons for organizational theory.

Research Site & Methods

To study the process of decoupling between rules and practice, I compare the implementation of a new safety management system in two industrial plants, both from the same company. My research design employs a mix of ethnographic observation, semi-structured interviews, and archival data for the generation of grounded theory (Glaser & Strauss 1967). I begin with a brief description of the sites, followed by more details regarding case selection, data collection, and analysis strategies.

For several reasons, Industrial Co (a pseudonym) is an ideal site to study the implementation of bureaucratic rules. To begin, industrial plants in the industry studied here are highly suited to the bureaucratic form of organization. Plants are large hierarchical organizations with highly stable operations based on technologies that have been in use for decades. Many of the elements of the bureaucratic form (e.g. Scott 2003) are highly visible, including strong hierarchical control, written rules, and a division of labor based on specialized knowledge. Knowledge is highly specialized and local: most unit operators and line managers have years of experience working in a specific process unit, and can recognize by sound and smell when a piece of equipment is not running correctly. Detailed procedures exist for shutting down and starting up units and individual equipment; operators have performed many of these tasks literally hundreds of times. Maintenance mechanics, in turn, perform routine tasks like bolting pipes and repairing pumps throughout their careers. The routine nature of work and high degree of coordination, in particular, are consistent with an environment where standard rules and formal structure are most likely to be effective (Perrow 1986). As a result, the failure of

rules at one of the two plants provides a unique opportunity to refine our understanding of the mechanisms that cause such failure.

Second, the particular circumstances of Industrial's recent history add to the appeal. In recent years, Industrial has suffered several accidents across its plants resulting in injuries to workers. As a result, managers at Industrial have faced pressure to improve the company's safety performance. The new safety management system is a direct response to these incidents. The increased attention to safety is important theoretically for two reasons. First, given recent events, actors at Industrial should be less likely to prioritize production over safety and normalize deviance. Second, attention to safety creates a unique opportunity for alignment between the interests of management and front line workers. Both plants are hazardous work environments, in which workers face risks of heavy machinery and exposure to dangerous chemicals, heat, and fires and explosions. As a result, safety is a major concern of workers and their unions. The potential for alignment between management and the workforce on the issue of improved safety presents an opportunity to study the sources of conflict independent of built-in differences in interests that might exist in other domains.

The New Maintenance "Work Control Process"

My subject for this paper is the implementation of a new safety management system in two of Industrial's plants. In recent years, "management systems" have proliferated across a wide variety of industries as a means to control risk in areas such as environmental performance, safety, and financial accounting. In particular, management systems are often held up as a means by which organizations can "self-regulate" or go "beyond compliance," thereby changing the regulator-regulated relationship and

improving regulated outcomes (Coglianese & Nash 2001, Gunningham et al 2002). The central idea behind management systems is that if rules are clear, compliance is documented, and actors are held accountable through a transparent audit process, important risks can be controlled. Management systems are part of a broader trend to manage risk that Power (1997) terms the “audit explosion.” In this paper, I focus on one particular component of Industrial’s management system: the new process to manage the risks of maintenance work. The new process, named the “work control process” (WCP)¹, was developed by the central corporate office and rolled out across all of the company’s operations. At the time of observation, implementing the WCP process was a major focus for much of the company.

Maintenance work is a substantial hazard and has been the source of several recent events in the industry. Maintenance work is performed by hourly maintenance mechanics, many of which are contractors. Typical maintenance jobs include inspecting and repairing pumps, compressors, valves, pipes, and tanks that transport and hold material. Because maintenance mechanics are not experts in the operation of the process units where work occurs, mechanics are dependent upon unit operators to explain their surroundings and safely prepare (i.e. shut down and drain) equipment prior to the start of maintenance work. Accidents can occur when equipment is not correctly de-energized and isolated from ongoing process, or when there are miscommunications surrounding the nature and location of work. Thus, the handoff between operations and maintenance presents a potential source of risk and error.

¹ A pseudonym

The WCP process is designed to standardize maintenance work and adopts many of the elements of bureaucratic control. Above all, the process is designed to ensure that all maintenance jobs follow standard rules for safe work. Under the previous process for maintenance work, mechanics were sent to units as needed, and operators and mechanics interacted on the spot to briefly document risks and ensure that jobs were prepared and executed safely (with more involvement from managers and safety experts as needed for higher risk work). In contrast, the new process introduces considerable planning and management oversight. Figure 1 illustrates the process for a typical maintenance job. Under the new process, trained experts in assigned roles visit the job site, determine the level of risk, and complete a job risk assessments as early as a week ahead of the job. Risk assessments must document job hazards, propose controls to mitigate hazards based on standard rules, and determine the residual level of job risk after all controls are in place. (Risk increases with both the magnitude of an accident and the probability of its occurrence). Managers in a supervisory role must then approve the risk assessment, with higher residual risk requiring a more senior manager's approval. Finally, prior to performing work, maintenance mechanics must perform a job "walkdown" with unit operators at the physical location of the work, to discuss job risks and verify that all controls listed on the risk assessment are in place, and that conditions have not changed in the time since the risk assessment was created.

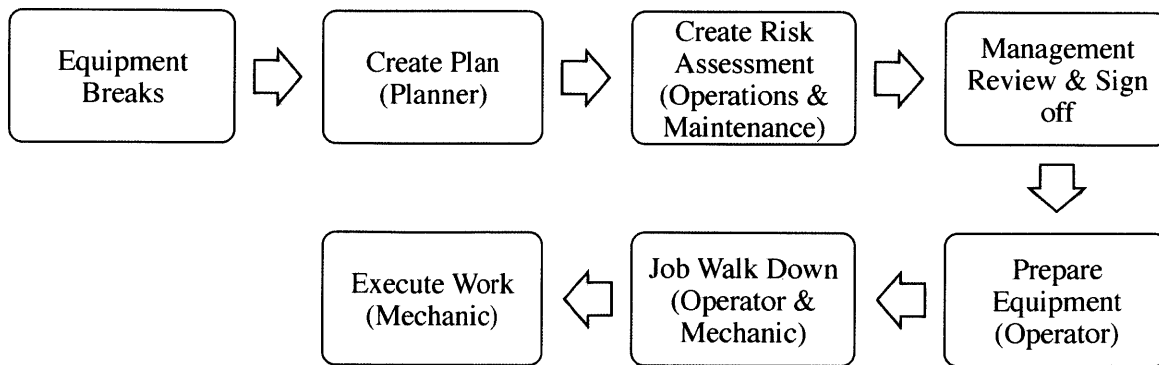


Figure 1: The Work Control Process (WCP)

As noted above, given the stability of plant technology and the routine nature of maintenance work, the WCP process should be highly effective at producing safe outcomes. First, the process facilitates coordination on safe work practices between managers, safety experts, and front line workers across a large organization. Second, the process should improve compliance with standard rules by limiting the normalization of deviance (Vaughan 1996). Due to increased oversight over the risk assessment process and controls to ensure compliance, actors lose some discretion to redefine anomalies as normal. Rules are established independently of local work cultures, and are thus more likely to remain consistent across time and place. Although operations managers may still advocate adjustments to rules to fit local conditions or particular situations, the WCP process is designed to limit such influence. In turn, given the nature of work, compliance with standard rules should improve plant safety. Table 1 lists several examples of controls that might be identified in risk assessments, listed on permits, and verified during walkdowns. All of these practices are widely recognized across the industry to reduce the risk of an accident.

In addition to enforcing standard rules top down, the WCP process is also designed to elevate anomalies that might otherwise be noticed only by the front lines. Risk assessments function very much like “checklists,” prompting actors to notice anomalies that they might otherwise miss. Checklists have been shown to reduce the rate of mistakes and accidents in a number of settings, such as hospitals (Haynes et al 2009). In addition, when actors are prompted to report and correct anomalies rather than normalize them, the organization can learn. Spear (2009), for example, describes how high performing organizations rely on front line actors to report deviations from standard practice. Front line actors have access to unique knowledge, and effective organizational learning depends on creating conditions where actors are able to share such knowledge (Edmondson & Tucker 2003). By providing clear rules and a structured environment to notice deviations from those rules, the WCP process should contribute to improved safety and reliability.

Risk	Typical Controls
“Breaking Containment”: Opening up a pipe, creating risk of exposure to substances	“Isolate” the point by shutting off flow, drain, test to be sure empty
“Spark Potential”: Devices such as power tools, vehicles may create a spark, igniting any hazardous gases in the area	Gas test area prior to work
“Working at Heights”	Install scaffolding, wear harness, barricade area below
“Confined Space Entry” – risk that air inside confined space is not sufficient to breathe	Gas test prior to entry, hole watch, rescue plan, wear respirator
Working with Tools	Be aware of pinch points, wear gloves

Table 1: Example Safety Risks and Controls

Case Selection

Despite mandating the implementation of the identical WCP process across all of its plants, Industrial has experienced considerable variation in the success of the policy. In this paper, I exploit such variation to develop theory on the failure of bureaucratic rules. Specifically, I compare the experience of two plants, labeled Beta and Alpha.

A comparison between two plants from the same corporation has many advantages over existing literature on bureaucratic control. First, such a comparison controls for technology. As described above, existing theories of decoupling in organizations emphasize that work technology has a large influence on the likely success of standard rules. By controlling for technology, I am able to provide a theory of the process of decoupling that is less dependent on pre-existing structural conditions.

Second, comparing two plants from the same company controls for the nature of the rule system itself. As noted, both plants are implementing an identical process. The specific design of rule systems can have a large influence on implementation outcomes. For example, Edelman (1992) argues that when rules are ambiguous, contain weak enforcement mechanisms, and emphasize procedures rather than outcomes, symbolic compliance is more likely. Here, the two plants are identical on these dimensions.

Third, the comparison here controls for the regulatory and institutional environment. Beta and Alpha both face similar pressures from the corporate organization to implement the mandated WCP process, including periodic corporate audits. In addition, both plants face similar pressure from government regulators. Past research illustrates that the manner of regulatory enforcement influences the success of self-

regulation (e.g. Short & Toffel 2010). Both Beta and Alpha were historically poor performers in the areas of health and safety, and both have made substantial progress in recent years on a number of safety metrics, including accident rates and equipment reliability (driven by a substantial investment in infrastructure at both sites).

Table 2 summarizes the similarities and differences between Beta and Alpha. In addition to the areas already noted, efforts were made to control for a number of other factors, including the presence of a union, and the use of contract maintenance mechanics. Table 2 also notes a number of differences between the two plants. Notably, Alpha is larger, has a slightly higher use of company mechanics, and made a number of different choices related to WCP implementation. None of these differences, however, can explain the divergence between the two plants. I describe the context of these differences in more detail in the case histories below.

	Alpha	Beta
Location	Outside urban center in the U.S.	Outside urban center in the U.S.
Technology	Industrial Plant, organized into process units	Industrial Plant, organized into process units
Work organization	Hierarchical	Hierarchical
Size of plant	Three times x	x
Use of contractor labor	Extensive (somewhat less so than Beta)	Extensive
Existence of Safety Department	Yes	Yes
Local Mgmt support for new WCP process	Strong – top priority beginning in August 2010 (somewhat lower priority earlier)	Strong – top priority beginning in December 2009 (somewhat lower priority earlier)
Timeline of WCP Implementation	Several iterations over 2006-2011	First iteration in 2006; Second in December 2009
Regulatory Environment	Strong pressure from regulators	Strong pressure from regulators

Past Safety record	Poor – significant improvement 2007-2011, including large infrastructure investment	Poor – significant improvement 2007-2011, including large infrastructure investment
Union status	Unionized	Unionized
Organization of maintenance	Mixed – some company mechanics are co-located with operators	Centralized – mechanics are not assigned to individual units
WCP staff structure	Hourly operators switched to day roles to write permits	Additional management positions added to write & approve permits
WCP format	Computer based (switch to computer based in 2009)	Paper based

Table 2: Comparison Between the Two Plants

Data Collection

As indicated above, data collection consisted of a mix of ethnographic observation, semi-structured interviews, and gathering of some archival documents. During initial visits to Beta in May 2010 it became clear immediately that implementation of the WCP process was the major focus of the organization, and that the opinion of the front lines was not always favorable. As such, I made efforts to collect a range of data to understand the perspective of both management and the workforce. In total, I spent seven weeks onsite at Beta between May and September of 2010. I spent more than 100 hours shadowing front line operators and maintenance mechanics (company and contractor) during day shifts, with an emphasis on the morning hours when the majority of maintenance work begins and the handoff between operations and maintenance occurs. To capture a broad cross section of the plant I shadowed in 5 different operations areas. While shadowing, I engaged in numerous informal conversations with individuals whom I met – these conversations often lasted 30 minutes or more, and were highly valuable. The pace of work provided ample opportunity to ask

employees for explanations and interpretations of events either during or directly after their occurrence. To gain the trust of the workforce, I did not take notes while shadowing, but jotted notes during breaks and wrote full-length narratives each evening before returning to the field.

To learn about the history of the policy and expand on observational data, I supplemented observation with more than 50 semi-structured interviews, half of which were with hourly employees (including operators, company mechanics, and contractor mechanics). Most interviews lasted around an hour, and the majority were recorded and transcribed. In addition to asking participants to describe the overall timeline and process of implementation, I asked participants to describe particular problems that they experienced while working within the WCP process, and how those problems were then resolved. Finally, to gain the management perspective, I attended more than 20 staff meetings and interviewed salaried employees from all functional areas.

I pursued a similar strategy at Alpha. I spent 8 weeks on site between January and June of 2011; in addition, I made shorter visits of a few days each in March of 2009 and September of 2010. In total, I spent a similar period of time – more than 100 hours - shadowing front line operators and mechanics (both contractor and company), again focusing on the handoff between operations and maintenance, and once again incorporating several different process units. In addition, I observed more than 30 separate risk assessment meetings involving an operator, a mechanic, and a safety expert, and interviewed 15 line and safety managers. As at Beta, lengthy informal conversations with hourly operators and mechanics were extremely valuable. At Alpha, I relied more

on these conversations to gain the perspective of the hourly workforce, and less on recorded interviews. Table 3 summarizes data collected at both plants.

	Alpha	Beta
Hours of Direct Front Line Observation	~100 (+50 hours of risk assessment meetings)	~100
Actors Shadowed	Operators, Maintenance Mechanics, Safety specialists	Operators, Maintenance Mechanics, Safety specialists
Number of Interviews	15	~50
Actors Interviewed	Managers, Safety Managers	Managers, engineers, operators, mechanics, Safety Managers
Weeks on Site	10 (January – June ‘11)	7 (May – September ‘10)

Table 3: Data Collected at the Two Plants

Data Analysis

Data were analyzed using standard methods of grounded theory building (Glaser & Strauss 1967). Observational data and interview transcripts, including notes compiled following all informal conversations, were assembled in Atlas/ti, a qualitative data analysis program. Analysis proceeded along several directions.

First, I coded interviews and informal conversations for all statements related to the implementation of WCP, including positive endorsements, recurring problems, and the timeline of management strategies or adjustments. I used this information to construct a case narrative for each site. Second, given the prevalence of implementation problems, I coded more specifically for the occurrence of problems, anomalies or disagreements, especially between rules and work conditions or between rules and the opinions of actors. I classified problems by their sources, and also noted how problems were resolved, if at all.

Third, I conducted a more detailed coding of observational data of the interaction between maintenance mechanics and operators at the beginning of maintenance work. Early on, it became clear that behavior during such interactions was an important source of variance between the two plants. As a result, I coded all handoffs between unit operators and maintenance mechanics according to whether a physical walkdown occurred: had the operator and mechanic signed the form at the operator's desk in the shelter, or did they meet at the actual job site? If the actors met at the job site, was there a discussion about job risks, or did the operator simply sign the form and move on? I also noted the identity of the mechanic (contractor or company), and where possible, a description of the work. I used the job descriptions to categorize work according to the level of risk, using the organization's official classification scheme, as listed in written documents. (When a walkdown did not occur, it was not always possible to obtain an accurate description). I then compared results between the two plants. The results were used to support qualitative accounts of the differences between the two plants.

Finally, I used both the case narratives and observational data to construct a dynamic theory of decoupling using the causal loop diagramming method (e.g. Sastry 1997; Sterman 2000; Repenning & Sterman 2002; Azoulay, Repenning & Zuckerman 2010). Causal loop diagrams have a long history in organization studies, and are an effective means to articulate an endogenous theory of change over time. Because my goal was to produce a theory of how decoupling may evolve to different degrees in highly similar settings, such an approach was appropriate. To construct the model, I first considered categories of problems and responses to problems that emerged from my field notes. Building on existing theory, I developed a simple causal model of the flow of

problems as they are resolved (or not resolved) by the organization. I next looked to the sources of problems, and expanded the model to capture those sources. Larger categories that emerged from interviews and informal conversations helped to fill in gaps. The resulting model captures micro-behaviors related to problem solving and rules as they are influenced by broader organizational policies and actions. I provide more details on the process of constructing the model as I present it below.

Overview of the Two Initiatives

The Work Control Process at Alpha

Alpha's effort to implement the WCP process began in 2006, as a part of a renewed effort to improve both the plant's reliability and safety performance. Although the WCP process was a corporate requirement, initially the process was not the first priority of site management. Site leaders had several additional concerns, including especially repairing and upgrading the site's long neglected infrastructure and improving the design and rigor of processes in a number of areas. As a result, the WCP process began as an initiative of the safety department. A team of former operations staff members and safety engineers, together with an outside contractor, began by developing an electronic tool that could be used to bring the site into compliance with one part of the WCP policy - that of job risk assessments. In other areas, the existing work process was temporarily amended. After 18 months in development, training on the new policy began and a pilot version of the electronic tool was rolled out to a small part of the plant. Given the variety of initiatives (also related to safety) ongoing at the time, however, the change

was not a success in the field. High workload on plant turnaround projects meant that many individuals were not available to participate in training, and middle managers were uncertain as to where to focus their attention. In addition, classroom training did not translate well into the field: operations and maintenance staff initially struggled with the basics of using the process.

Several months after the first rollout, site leadership changed, and the new leadership quickly noticed problems with the WCP process. The electronic tool produced lengthy risk assessments for each maintenance job - some in excess of thirty pages - yet did not appear to achieve its objective of controlling risk. Many of the risks included on risk assessments were minor (e.g. "Slips, trips and falls") and important risks specific to individual jobs were sometimes not listed at all. When senior leaders spoke with workers in the field, often workers could not identify the most important risk that they faced in their immediate work. In addition, the overall process was not generating high quality face-to-face discussions in the field - one of its central goals. Given these problems, plant leadership decided to put further rollout of the electronic tool on hold.

The hiatus did not last for long, however. Several months later, Alpha was faced with a corporate safety audit that included an assessment of the site's compliance with the WCP process. Needless to say, Alpha's performance on the audit was not encouraging. Auditors identified shortfalls both in the written policy and in behaviors and understanding in the field. As a result, WCP implementation immediately became a priority of senior leadership. During the first part of 2008 site leadership laid out an aggressive three-month timeline to write a fully compliant policy and roll it out across the

entire site. To simplify the rollout, a paper-based system was introduced with the intention of migrating to the electronic tool at a later date.

As the site became accustomed to the process, many of the problems from the first implementation reemerged. These problems, described to me in interviews in the spring of 2009, matched many of the problems that I would observe in the field two years later. Above all, the site struggled with the logistics of the flow of paperwork. In theory, jobs were planned and risk assessed more than a week before work would begin, so that work crews and unit operators could easily retrieve paperwork, review and discuss job risks, and complete a final “shift” evaluation on the day of the job. In practice, this process often broke down. In the case of “break-in work” - high priority work that is unplanned - units had to scramble to complete paperwork on the spot. (Break-in work remained a higher than desired share of work in many units). Even for planned work, risk assessments at times contained errors or were incomplete. In such cases, work was delayed for hours while corrections were made and new signatures obtained. The risk assessment process itself was problematic: due to inexperience and the lack of a library of pre-created risk assessments to draw upon, risk assessments were time consuming. (Actors commonly complained: “we spend two hours on a risk assessment for a 20 minute job.”) The volume of paperwork was also high, due to the detail required: individual jobs might require 5 or 6 different risk assessments, and a single operating unit (with a staff of 2 or 3 dedicated to paperwork) might be responsible for completing more than 100 in a week. (Most were not of the two-hour variety). Meanwhile, problems on the front lines continued: workers did not always understand the risks of their work, and

face to face conversations between unit operators and maintenance mechanics did not always occur.

Given these difficulties, by 2009 the WCP process came to be viewed as a serious drag on efficiency. The stated goal was to improve the application of the process so as to become “safe and efficient.” Efficiency was important not only for profitability: much of the plant still faced a large backlog of maintenance work, and completing such work was seen as essential for improved safety. In part due to time pressure, inconsistencies between units grew as individual unit superintendents adapted the policy to fit their beliefs and needs. Partly to improve efficiency and make internal audits easier, by early 2010 the entire site moved to the electronic risk assessment system developed earlier (and still in use in the two original pilot units).

Meanwhile, pressure from the corporate office continued. Although the overall rate of incidents had declined, the rate remained high, and many could be attributed directly to breakdowns in the WCP process. Safety remained a huge point of emphasis up and down the organization. While the shift to the electronic system brought some improvements, it also added some compliance challenges. In the years since the electronic system had been created, the corporate office issued a revised and more detailed version of the WCP process. Unfortunately, the output of the electronic tool did not always match what auditors expected. Between 2009 and 2011, the site continued to adapt in an attempt both to satisfy corporate expectations and to improve the quality of risk assessments in the field. At first, individuals completing risk assessments were instructed to be exhaustive and list as many risks and controls as possible. Due to continued concerns regarding quality, however, individuals were soon told instead to

focus on completing a thorough job walkdown and listing only those risks that were most important. Next, units were given training on how to identify risks by considering potential sources of energy. Finally, the focus turned to the language used: individuals were forbidden from using drop-down menus in the software and required to write out each hazard and control individually, using clear and precise language. Throughout this time period, the site became weary of the constant change. Each change required a new learning period, and meant that units could not reuse and adapt risk assessments that had been created earlier, thereby exacerbating time pressures.

By mid-2010, both plant management and the corporate office regarded Alpha's continued problems with the WCP process as a serious risk. In response, the group charged with overseeing the process was moved from the safety department to operations, and a senior manager was brought in to lead a renewed effort. The move gave the central WCP team greater authority to achieve compliance in the units. A major effort was made to improve the quality of risk assessments for the highest risk work by training and expanding the centralized team that facilitated these meetings. Unit superintendents were required to spend time in their units working with their employees on the process and conducting audits. Consistency between units increased and quality improved, as reflected by improved performance on a corporate audit in early 2011. In addition, by 2011 the rate of incidents had declined substantially, possibly due to improvement in the WCP process, but also due to the cumulative effect of five years of work on a broad range of initiatives.

Yet, despite improvements, the link between paperwork and behavior in the field remained elusive. During my fieldwork in 2011, I observed many of the same issues

described above. Units struggled with the logistics of the process, and errors, rework, and planning breakdowns continued to undermine efficiency. Lack of knowledge and disagreements over interpretation continued, both in the management and hourly ranks. Most importantly, many front line workers continued to resent and resist the process. WCP was widely viewed as a form of “lawsuit protection” rather than a process to ensure safe work. As a result, workers at times failed to conduct face-to-face discussions at the job site as required by the process, especially for medium to lower risk work. During my hours of observation, job walkdowns occurred less than 50% of the time, as shown in Table 4. Although risk assessments performed in the planning stage were often of high quality, unless the same individuals were present to conduct the work, learnings from the discussion were lost; typically, the evaluations that maintenance crews filled out at the start of shifts were of very low quality. Finally, if a job permit did not exactly match some portion of the work, maintenance crews were faced with the uncomfortable choice of either deviating or delaying work for hours so that a new permit could be created. As a result, workers preferred that permits remain vague, and did not suggest improvements to the process unless the issue was considered serious.

For all of these reasons, a large degree of decoupling persisted between the ideal of the WCP process and actual work practice. Such decoupling existed despite enormous effort over a period of five years on the part of the organization to align behavior, and a strong interest on the part of both management and the workforce in safety. Decoupling was not complete: given the emphasis on audits and strong norms in support of many safety rules, many activities did follow standard practice. As a system of control, however, the WCP process at Alpha had many flaws.

	Alpha					Beta				
	Jobs	Jobs Requiring Walkdown	Physical Walkdown	Walkdown with Discussion	Percent Walkdown & Discussion	Jobs	Jobs Requiring Walkdown	Physical Walkdown	Walkdown with Discussion	Percent Walkdown & Discussion
Total	43	43	22	17	40%	18	14	13	13	93%
Contractor	33	33	20	16	48%	15	11	10	10	91%
Company	10	10	2	1	10%	3	3	3	3	100%
High Risk	8	8	8	7	88%	5	5	5	5	100%
Medium Risk	11	11	5	3	27%	4	4	4	4	100%
Low Risk	10	10	5	4	40%	8	4	4	4	100%
Risk Unobserved	14	14	4	3	21%	1	1	0	0	0%

Table 4: Comparison of Walkdowns Observed at Alpha and Beta

The Work Control Process at Beta

The WCP process began at Beta in 2005, in response to the same original corporate mandate that Alpha faced. As at Alpha, the process was originally the domain of the safety department. Unlike at Alpha, however, Beta's implementation was paper-based from the start. For most jobs, operators and mechanics would complete a risk assessment by hand on the morning of the job and then present the risk assessment for a supervisor's signature. This arrangement provided considerably greater flexibility than the version that was adopted at Alpha in 2008, and later at Beta. Because operators completed risk assessments on the spot, maintenance crews could be assigned as needed, including on short notice, without the planning and coordination required in the later version of the policy.

Beta's experience in the first few years of the policy was similar to Alpha's. Over time, practices between different process units began to vary substantially, as adherence to the policy degraded. For example, while the original policy called for a separate risk assessment for each job task, in parts of the plant risk assessments were eventually

combined onto a single form for each job. Maintenance spending was high, but reliability was low, as the site responded to one emergency after another. More importantly, the process was not producing safe outcomes. Beta's safety problems were not lost on site management: in the spring of 2008, following a string of accidents, the site manager called a "safety crisis" and embarked on a sustained effort to raise safety performance.

The period between 2007 and 2009 was one of substantial change at Beta. As at Alpha, a major focus of improvement was infrastructure: during 2007, Beta underwent a major plant turnaround, and maintenance headcount remained elevated in the following years as the site began to work down its backlog of deferred maintenance. Both Alpha and Beta also invested in workforce training, extensive engineering reviews of unit safety, and improvements in a wide range of work processes, including especially unit operations.

Beta's approach to improvement differed from Alpha's in a couple of important ways, however. First, for much of the period between 2007 and 2009, the WCP process remained on the back burner. The site continued with the old version of the process while focusing on other priorities, and was not compelled to introduce the full process as soon or in such a rushed manner. Second, Beta made an especially successful effort to involve the workforce in its overall change effort. In particular, the site introduced a "near miss" program and actively encouraged workers to submit problems by offering prize drawings. The number of problems reported increased from 100 a year before the program to more than 8000 after. Although not all of the items were of high quality, many were. Management implemented an improved system to monitor action items, and

workers gradually began to raise issues and pressure management if they were not addressed. In addition, under the “safety crisis,” managers at all levels made a concerted effort to discuss safety and enforce safety rules. Whereas deviations in some areas were previously tolerated or even encouraged, especially by front line supervisors, there was now a strong expectation that rules be followed. As one hourly operator explained in an interview:

“They just require it. It’s simple. [Either be safe or they will] escort you out the gate. Wear your harness where you’re supposed to, [or] you can’t work here. And they’re serious about it. They just don’t talk safety, they mean it.”

In turn, workers began to play a role in reminding their peers to observe rules, as I observed on many occasions in the field. The increased vigilance was reflected in performance: by the later part of 2009, safety incidents had become rare events.

Thus, by the time the revised version of the WCP process was implemented in December 2009, Beta was already a much safer place to work, and many of the rules that the system was designed to highlight and enforce were already well understood by the workforce. In addition, the site spent most of 2009 laying the groundwork for the new policy in the management ranks. In contrast to Alpha, ownership of the WCP process was moved from the safety department to the operations department *before* the implementation, rather than after. Operations superintendants agreed on agreed on several important issues of interpretation before the rollout, eliminating the potential for inconsistency later. Finally, after studying the process, Beta made the decision to dedicate additional salaried staff to important roles in the process. (At Alpha, these duties were spread among managers with roles in other processes, and hourly operators pulled off of shift).

Yet, despite more favorable conditions at the time of rollout, Beta experienced many of the same challenges that Alpha faced in the first months of implementation. As at Alpha, classroom training failed to prepare the workforce for the logistics of executing the process, and the initial confusion alienated many in the hourly ranks. The complexity of the process, including the challenge of coordinating the flow of paperwork between planners, operations staff, and maintenance staff, led to errors, rework, inconsistencies between process units, and further resentment. For example, operators soon began to notice occasional errors on job permits and risk assessments that suggested that no one had even visited the job site during the planning stage. On the planning side, planners and operations personnel at times struggled to stay ahead of the volume of work. Risk assessments were often vague and used the same recycled phrases. Some operations staff disliked the delay required to plan and schedule non-emergency tasks and the requirement that equipment be taken out of service early, preferring the flexibility of the previous approach. Opposition was especially strong from experienced company mechanics: whereas previously these mechanics had more latitude to “troubleshoot” at the jobsite, now each task was spelled out in detail ahead of the job. As at Alpha, errors and planning breakdowns at times delayed work and left mechanics waiting for hours without a job.

Although Beta and Alpha experienced many of the same problems with the WCP process, the response to these problems - especially on the front lines - differed in important ways. Rather than actively resist the process, operators and mechanics began to fill the gaps themselves. The WCP process was seen less as a sign of management coercion - a way to shift the blame in the event of an accident - and rather as a sign of

management weakness - an indication that despite extensive efforts to plan, safe work still depended on the skill and knowledge of committed operators and craft mechanics. Thus, hourly workers described the process as a “game of telephone” in which important information might get lost, or a paperwork requirement that didn’t change the job that they needed to do.

This sentiment was manifested in at least two ways. First, in contrast to Alpha, workers at Beta insisted on completing physical job walkdowns. As shown in Table 4, during my hours of observation workers completed walkdowns almost universally, including in cases when a walkdown was not required. As described above, job walkdowns are an essential component of the WCP process: walkdowns allow mechanics and operators to share important knowledge related to job risks, and increase the chances that problems are noticed and corrected. Second, as I will describe in more detail below, workers often worked within the WCP process to correct errors, report problems both with the process and with individual jobs, and resolve interpretation challenges.

Together, these activities helped to create a system that, while often imperfect, produced a greater degree of coupling between safety rules and work behaviors. By August 2010 - only the 9th month of the revised process - I often arrived at a process unit to observe a maintenance schedule that was closely followed and operators highly engaged in ensuring that all mechanics understood the risks of their work. Operators began to describe the benefits of the process: in particular, many appreciated the newfound certainty of the schedule. On most days, there was no longer a rush to adapt to whichever maintenance crew arrived: everyone knew several days in ahead what work was coming.

A Model of Rule Implementation

How do we explain the divergent outcomes between Beta and Alpha? As the above case histories make clear, existing explanations for decoupling between rules and practice are not satisfactory in distinguishing between Beta and Alpha. First, decoupling at Alpha is clearly not a deliberate choice of management. While Alpha achieved ceremonial compliance early on, the site continued to face pressure based in part on poor safety outcomes. The WCP policy contains strong enforcement mechanisms: when audits revealed poor compliance on the front lines, Alpha continued to invest sizable resources in repeated attempts to align behavior with the design of the process. Second, failure at Alpha is not a consequence of inherent opposition to rules from workers or status groups. During the course of the implementation effort, workers experienced several accidents due to breakdowns in the process. Safety at Alpha was a very real concern. Third, the presence of profit or production pressures is only part of the story. While such pressures were a source of resistance by middle managers at Alpha, they were also present at Beta, and were counterbalanced by a strong imperative to implement the process at both plants. Alpha also made substantial improvements in other areas of safety and operations during the same period. Finally, decoupling cannot be attributed entirely to the normalization of deviance. Very often, actors were aware of rules and actively contested such rules. How did the WCP process become a source of resistance more so at Alpha than at Beta?

In the next sections, I develop a dynamic theory of rule implementation in organizations using both the case histories and close analysis of observational and

interview data from both plants. I begin by considering the impact of the process on the routine work of front line actors. I next illustrate how broader policies and the particular context of implementation influence the dynamics of the two plants. Finally, I conclude by drawing several general lessons for organizational theory.

The Basic Structure of Organizational Control

To form the basic structure of the model, I build on the work of Vaughan (1996, 2005). Vaughan conceives of organizations as facing a stream of “problems” or “anomalies” that are noticed, categorized, and possibly acted upon. The “trajectory” that anomalies follow has important implications for the management of risk: in particular, when certain anomalies are left uncorrected, they may form latent conditions that cause future accidents (Turner 1978, Vaughan 2005). As a result, organizations attempt to influence how anomalies are classified and resolved through control systems, including surveillance technologies, rules and procedures, and training.

Figure 2 captures a portion of Vaughan’s theory using the language of causal loop diagramming (Sastry 1997; Sterman 2000; Repenning & Sterman 2002). Arrows denote a causal relationship: a plus sign means that an increase (decrease) in the independent variable causes an increase (decrease) in the dependent variable, whereas a minus sign means that an increase (decrease) in the independent variable causes a decrease (increase) in the dependent variable. At the center of the diagram is the variable “problems encountered.” As organizational actors complete work activities, they encounter a series of problems that must be classified and resolved in some manner. Actors face a choice in

how to respond to anomalies. Two choices are presented in Figure 2, represented by two feedback loops: problems are either corrected (“fix it”), or normalized (“normalize it”). In the case where problems are corrected, an increase in the flow of problems leads to an increase in problems corrected, thereby bringing the number of outstanding problems into balance. (The “B” represents a balancing, or goal-seeking feedback loop). Alternatively, actors may determine that a problem is an acceptable risk and choose to proceed without correcting it. Because the link between uncorrected problems and incidents is weak and delayed (as illustrated by the dotted arrow), the decision to classify a problem as an acceptable risk is often validated. The problem is normalized and no longer classified as deviant. The normalization balancing loop is a second mechanism by which the flow of problems is brought into balance: as the number of problems increases, more problems are normalized, leading to fewer deviant conditions and fewer problems surfaced in the future.

The variable “capacity to resolve problems” plays a crucial role in these dynamics. As Vaughan argues, the process of responding to problems is *capacitated*: given production pressures and limits to the flow of information, organizations have the capacity to acknowledge and resolve only so many problems. As a result, if the flow of problems exceeds the capacity to correct problems, organizations will often normalize deviance such that the flow of problems is brought into balance.

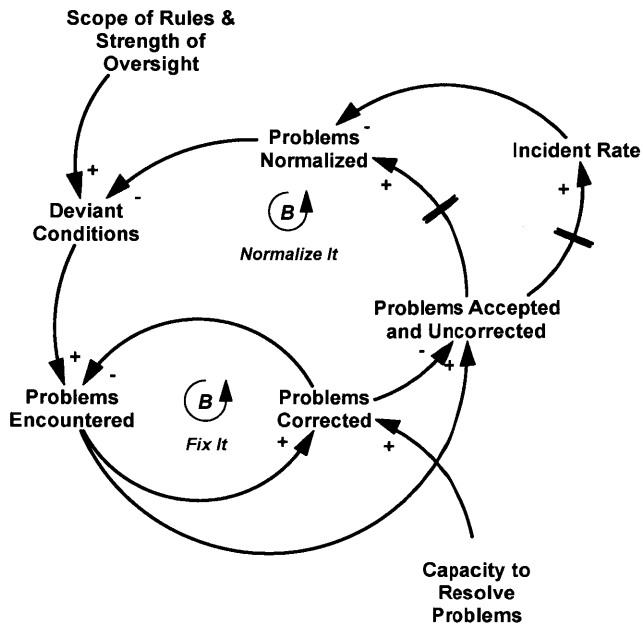


Figure 2: The Basic Structure of Organizational Control

The goals of the WCP process, and bureaucratic control generally, are well represented in this diagram. Through detailed rules and oversight - represented by the variable “scope of rules and strength of oversight,” the organization hopes to influence how problems are classified and the responses that actors take. In my observation of work, very often the process worked in exactly such a manner. An actor noticed a problem, classified the problem as deviant, and corrected it. At times, oversight - provided through the formal risk assessment process - caused actors to reclassify as deviant a condition that they might otherwise have accepted. For example, one afternoon at Alpha I observed a risk assessment for a job that involved cutting and welding a new section of pipe onto an existing line. Welding carries substantial risk: the open flame could ignite any nearby vapors in the air and cause serious burns to the welder. As a result, controls required by the WCP process are designed to ensure that dangerous

vapors are not present either in the air or in equipment where welding will occur. During the risk assessment process, actors are required to visit the job site and search for problems that could increase the risk of vapors being present. On this afternoon, I observed exactly this occurrence. During the job site visit, the welder noticed an additional line (pipe), directly next to the line where he would weld. Would the additional line be cleared of material, he asked? The material in this section of the unit was light and highly flammable, and so could easily escape and cause an accident if there were an undiscovered leak. As it turned out, the operators had not planned to isolate the nearby line (and had not done so in the past for similar work in the area), but agreed to suggest the change to their supervisor and include the extra step in the job preparation. The risk assessment now included an additional control to isolate the nearby line. The work crew, on the day of the job, would be responsible for ensuring that this control was in place. On this occasion, the formal risk assessment process caused a problem to be noticed, classified as deviant, and corrected.

Expanding the Model: First and Second Order Improvement

While I often observed problems that could be corrected in the normal course of work, on many other occasions responses were not immediately available. For example, had the welder noticed the above problem on the day of the job, rather than during the planning stage, resolving the problem would have required delay and rework. On other occasions, actors became aware of sources of problems that extended beyond the immediate context. In my observation, these constraints had a large impact on the experience of working within the WCP process.

To more fully capture the process of responding to problems, I draw on literature from organizational learning. Research shows that to fully learn from problems and events, organizations must actively make efforts to search for and correct root causes (Carroll et al. 2002, Spear 2009). In the learning literature, the distinction is sometimes made between “first order” problem solving that addresses proximate causes, and “second order” problem solving that resolves underlying causes and prevents re-occurrence (Tucker et al. 2002). While front line actors confront many problems in the course of work, they often lack the time, resources, collaboration networks, or sense of security necessary to seek out more lasting solutions. For example, in a study of hospital nurses, Tucker et al. (2002) find that nurses only rarely raise problems with colleagues and superiors and instead rely on temporary workarounds that effectively normalize deviance.

Figure 3 extends the model to more accurately reflect the process of correcting problems. The variable “problems corrected” refers to immediate resolutions that can be achieved in the normal course of work, as in the above example. The process of searching for more fundamental solutions is represented by the balancing loop “improve it.” When actors use problems as an opportunity to search for and resolve root causes, the rate of future problems decreases. For example, in the welding job above, actors could amend a template that is used for later jobs, inform others in different units to look out for similar problems, or search for opportunities to complete welding work ahead of time when the entire unit is shut down and drained. If these activities are undertaken, mechanics during future risk assessments are less likely to discover a potentially dangerous line that is not already included in the job plan.

Unlike immediate solutions to problems, however, the effects of second order problem solving are *delayed*. Efforts to document and share a response to a particular problem require time and resources, and won't reduce the rate of future problems until improvement activities are completed or until a similar problem presents itself. Once again, these delays are represented using dashes. To represent the accumulation of improvement activities, I introduce the term “capability,” adapting a concept from Repenning & Sterman (2002). A capability is an accumulation that builds or depletes over time and that has a positive influence on performance (Dierickx & Cool 1989, Teece et al 1997, Schreyogg & Kliesch-Eberl 2007); in this case, performance is understood as the relative absence of problems or anomalies that create operational risk. When actors invest in removing root causes, after a delay the capability of the organization is increased.

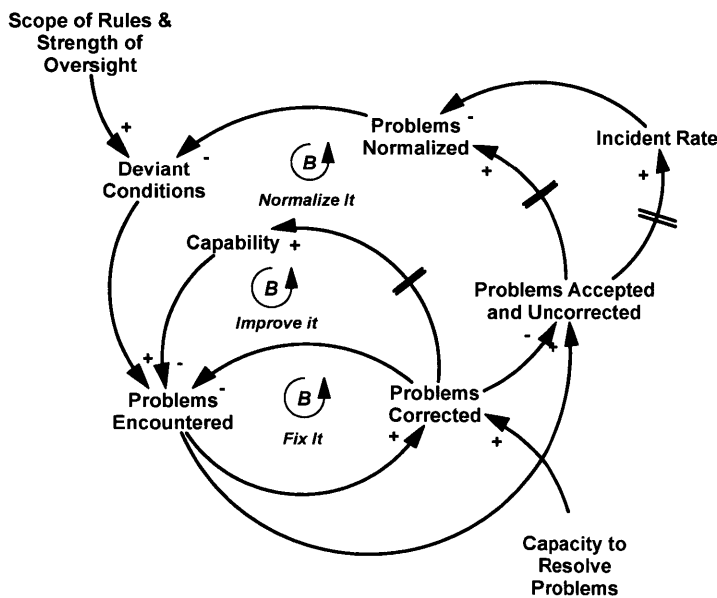


Figure 3: Adding Capability

The concept of capability corresponds well to the root causes of problems that emerged from fieldwork. In my analysis, I identified three common sources of problems that each share the basic qualities of a capability:

1) *Infrastructure*. Many of the problems that I observed or that were described to me in interviews had some basis in the state of physical infrastructure. Infrastructure acts of a source of problems in at least three ways. First, latent problems in the design of equipment can introduce risk and increase the challenge of applying a standard approach to work. For example, several problems could be traced to shortcuts taken in equipment design many years prior. Prior to most maintenance jobs, operators and mechanics must verify that pipes are clear of hazardous material. Usually, extra valves exist that allow workers to perform such verification. (A small “bleed valve” is left open next to the work location; if material does not flow out, then workers know that the line is depressured). On occasion, however, the layout of equipment does not allow for a full verification, due to past oversights in design. Exceptions like these present an anomaly in the risk assessment stage, and require a more thorough review, more detailed rules to handle contingencies, and - if work proceeds - the acceptance of a higher level of risk. At times, the impact on risk can be substantial: during one of my visits to Alpha, a group of mechanics was tasked with removing a relief valve in the absence of positive isolation where - according to them - the pressure in the pipe could rise to 1800 lbs. Even where individual designs are sound, inconsistencies in equipment between units or between plants can present anomalies that make a process like the WCP process more complex and resource intensive. As one environmental manager explained, because many of Industrial Co’s plants were acquired at different times from different legacy companies

(Beta and Alpha are no exception), many latent inconsistencies in design remain.

Proactive efforts to find and correct design flaws or inconsistencies can reduce the rate of future problems.

Equipment defects due to wear and disrepair are also a common cause of problems. For example, I observed one risk assessment at Alpha for an emergency repair of a metal fan box that had begun shaking as the fan was deployed during unit startup. Once again, past shortcuts in design and construction were partly to blame: the box looked as if it had been constructed in haste. Unfortunately, the timing of the breakdown could not have been worse: the fans were absolutely needed to cool material during the startup process, and bringing the unit back down also posed substantial risks. As a result, operators had to slow the speed of startup so that repairs could be completed during a window of time when the fan was not needed. Due to a latent defect in infrastructure, a routine job now presented several problems with regard to the management of risk: in particular, mechanics would now be required to work in the unit during a startup, the most dangerous time to be present in the unit. In general, latent equipment defects can cause unexpected changes in job scope, introduce complications that increase risk, or disrupt maintenance work plans. In all cases, problems are introduced that must be resolved through the risk assessment process. Once again, these problems can be avoided through proactive efforts to find and correct equipment that is in disrepair.

Finally, the general state of infrastructure - beyond specific defects - has an important influence on the rate of problems surfaced. As described, the WCP process is built on the ability to plan maintenance work so that work can be risk assessed and reviewed well ahead of the start date. When units face a large amount of unexpected

“break-in” work, planning becomes more difficult and unexpected problems are more likely to arise. The overall state of infrastructure has an important impact on the prevalence of such break-in work (Carroll et al 1997, Lyneis, third essay of this dissertation). When unplanned breakdowns are common, organizations are easily trapped in a cycle of increasing reliance on reactive work (Repenning 1999), with important implications for the management of risk.

Thus, infrastructure functions as an important capability. The state of infrastructure has a direct effect on the rate of problems that emerge in the management of risk. Moreover, infrastructure is an accumulation that builds over a long period of time and is adjusted only at great cost. In the case of these plants, maintenance and design decisions can influence operations years - if not decades - into the future. When actors respond to problems by investing to resolve underlying defects in infrastructure, gradually the rate of new problems will fall.

2) *Knowledge*. A second common source of problems was inconsistency in the knowledge of actors. Like infrastructure, knowledge is an accumulation that influences the rate of problems surfaced and that builds over time as actors learn from events and develop common routines (Feldman & Pentland 2003). When actors understand the risks of work and share effective responses that treat typical or even highly specific conditions as deviant, problems related to misclassification of risks, disagreement, and rework are fewer. In part, knowledge is captured in the library of risk assessments that actors draw on when planning new work. When actors can quickly pull up an accurate and detailed risk assessment for a specific job based on expert discussions that occurred in the past, the potential for error and rework is reduced, and actors can instead focus on novelties or

further improvements to job design. Given that most jobs are recurring (i.e. a specific pump will need maintenance several times per year), a quality library of risk assessments is a significant resource. When actors use problems to update this library, the capability of the organization is gradually improved.

Many problems that I observed during work can be attributed to a lack of knowledge. In particular, the lack of knowledge of those completing risk assessments often caused rework later in the process. Consider the example of the welding job above. In this example, neither the operators nor their manager thought to isolate the additional line as a part of the job preparation. Had these actors seen more training or experience in identifying sources of energy, or had the job plan been amended in the past, the problem would not have occurred. At times, delays caused by rework can be considerable. For example, one manager at Alpha described the problems that his unit was having with maintenance work performed by specialized instrument mechanics. Because individuals writing the risk assessments did not understand how to do the work, when the morning of the job arrived, permits had the wrong tools or were missing steps. Given the usual amount of activity in the mornings, fixing errors sometimes caused delays of several hours or more. Gradually, as risk assessments were crafted to repair specific instruments, the unit learned to avoid some of these errors.

Knowledge is also reflected in the consistency of interpretations across units. Because many maintenance mechanics work in multiple units, craft workers notice when risks are documented and controlled differently at different times or places. Such inconsistencies are another source of problems: when mechanics notice the anomaly, they

must either normalize the difference or raise the issue until the different units arrive at a common understanding.

It should be noted that the influence of knowledge on the rate of problems surfaced is not always unidirectional. Expert knowledge can also cause actors to challenge existing interpretations and create new problems. Nor is a decrease in the rate of problems surfaced always a positive outcome for the management of risk. Capabilities erode over time, and ultimately organizations may require a stream of problems to ensure that learning is continuous. When organizations develop common approaches to risk, they lose some ability to see the limitations in those approaches (Stark 2009). I do not argue that organizations should ever strive to eliminate problems entirely - instead, even as they eliminate some problems they might benefit from deliberately creating others. Nevertheless, many of the problems that I observed - like tools listed incorrectly on a risk assessment - provide no value and only take resources away from more substantive discussions.

3) *Social Relationships*. A third capability is the social relationships that exist between actors, and especially between managers and workers. Social relationships act in concert with knowledge and infrastructure to reduce the flow of problems. Often, strong relationships that span hierarchical and functional boundaries are necessary to fully resolve problems and prevent the normalization of deviance. For example, communication channels between managers and workers built on trust can spur effective investment in infrastructure and the development of consistent routines to correct deviance early on. Teams that build relationships across functions can often develop novel solutions to improve compliance (Huising & Silbey 2011, Pires 2011). In my

analysis of field notes, the absence of such relationships - especially at Alpha – contributed to actors’ failure to resolve problems. Like infrastructure and knowledge, relationships become stronger over time as actors develop experience in the joint resolution of problems.

One example helps to illustrate the potential for social relationships to resolve, and ultimately prevent problems. On one occasion at Alpha, I observed a maintenance crew that was repairing a large fan housed in an overhead box in the middle of a process unit. After replacing a part, the group was attempting to move the fan back into its usual position by pushing up on the shaft that was partly exposed below the box. The shaft, however, would not budge. After a few minutes of pushing, the group improvised a solution. One individual walked over to another part of the unit to retrieve a rolling workbench, and placed it underneath the shaft. Another individual collected several pieces of scrap metal and began piling these pieces on top of the bench, until the top piece was touching the shaft. The mechanics then lodged a jack between two pieces of metal, and began using the jack to apply upward pressure on the shaft, until the fan moved into place.

In this example, the mechanics faced a clear “problem”: the fan shaft would not budge using the normal tools prescribed for the job. Although the mechanics could think of an alternative, their improvised solution was not included in the job risk assessment, which must list all tools used for the job. Thus, moving ahead was a form of deviance. Their approach, although effective, introduced risk: What if the pieces of metal had buckled under the pressure? Later, when I relayed this story to an expert from the WCP central group, he explained to me how the group might have approached the problem

differently. Fans like the one in question existed throughout the plant, and workers performed maintenance on them frequently. Why not engineer a system that could be used repeatedly to help push shafts back into place? Experts in the WCP process emphasize the value of engineering solutions that eliminate job risks. A system that was designed and tested would eliminate many risks posed by an improvised system. Yet, achieving such a solutions would require initiative beyond the usual daily routines. Mechanics would have to delay work and report the problem to supervisors, and work with both managers and the engineering staff to implement a solution. Managers would have to support the effort and tolerate time away from more urgent tasks. None of these responses were taken on this day. When actors develop problem-solving relationships across functional and hierarchical lines, those relationships are an asset in the effort to manage risk.

The Dynamics of Decoupling: The WCP Process at Alpha

The model developed above provides an excellent starting point to understand the dynamics of decoupling. In the following sections, I extend the model to illustrate how the broader policies of the organization influence bureaucratic control as it is experienced by front line workers, producing decoupling on the one hand, or relative alignment between rules and practice on the other.

To recap, the basic impact of bureaucratic control is to create a stream of “problems” that are experienced on the front lines. These problems include problems in the interpretation of rules, problems managing the flow of paperwork, problems caused

by latent defects in infrastructure, and gaps between established behavior patterns and the expectations of rules. Problems are produced through the interaction between the organization's underlying capability and a rule system that elevates inconsistencies and anomalies to the attention of organizational actors: when the state of infrastructure, knowledge, and social relationships are stronger, fewer problems are created by standard rules.

My basic thesis is as follows. When strict rule systems like the WCP process are introduced in the absence of a strong underlying capability, the resulting flow of problems can overwhelm the capacity of the organization to resolve those problems, leading to unintended consequences that undermine the effectiveness of the rule system. In contrast, when underlying capabilities are stronger, organizations are better able to resolve problems and rule systems can instead spur improvement and alignment. External pressures that create an expectation of conformity where underlying capabilities are lacking can therefore act as a catalyst for decoupling dynamics, even where rules might otherwise be supported. The different trajectories, I argue, are in evidence at Alpha and Beta.

At Alpha, capabilities were weak in all three areas at the time of implementation. Although the site had begun to make investments in infrastructure during the previous years, the volume of deferred maintenance work remained large, as reflected in poor reliability. Approaches to risk varied widely across units and work pressures at times created an incentive to cut corners, as reflected in high incident rates. Tensions between managers and workers and between functional groups remained.

The challenge of poor reliability was a common theme in interviews. The point is perhaps best illustrated by a quote from one superintendent who happened to be in charge of two different units - one that was older and had equipment that was constantly breaking down, and the other that had been recently constructed and was in excellent condition (an outlier at Alpha). Despite sharing the same maintenance workforce, this superintendent observed very different results on his audits of the WCP process:

“One area, we have very little work. So, the risk assessments were really good. I’d go out there, and everything was as it said. I would ask the [operator] what the job was, just to see if he knew what was going on. I would ask the [mechanic]. They would identify the LOTO, they knew the hazards – it was really good. The other area there is a massive amount of work going on. So what I would find is, a lot of, ‘oh well I knew that’... but we didn’t document it on the shift permit.” - Operations Superintendent, Alpha

During my days on site - more than two years after the first full implementation of the WCP process - the impact of low reliability and deferred maintenance on the process remained abundantly clear. Many middle managers reported struggling to create high quality risk assessments for such a high volume of work. Emergency unit shutdowns - a reflection of a reliance on reactive maintenance - were not uncommon. (On several occasions, my visits to units to shadow operators or mechanics were postponed by these events.)

Despite the high volume of deferred maintenance, the reliance on reactive work, and the absence of consistent routines to manage risk, Alpha was compelled in early 2008 to implement the full WCP process following the failed corporate audit. Immediately, “problems” were created. The volume of problems caused tension with the demands of work, causing front line actors and middle managers to occasionally resolve problems by cutting corners and normalizing deviance from rules. The legacy of corner cutting was

clear in my observation of risk assessments in 2011, when efforts by the central WCP group to enforce rules were finally finding success. For example, one afternoon I observed a risk assessment for a “confined space entry” job where a pipe with live process flow would also be present inside the space. Entry into confined spaces can pose serious hazards: for example, if the air inside is not safe to breathe, persons who enter could collapse and die. When a live pipe is present, the risk is increased because a leak could affect the condition of breathing air. As a result, the corporate policy requires that all measures be taken to shut off flow prior to the work. If for some reason flow cannot be isolated, added precautions and approval from more senior managers is required. During this risk assessment meeting, it was clear that neither the mechanic nor the operator understood this rule. When the facilitator from the central group asked: ‘can you shut down the flow inside the pipe?’, both were reluctant. This very same mechanic had performed the job the previous year (in 2010 - when the rule certainly was in place) without shutting off flow, and the operator was worried that shutting flow would disrupt operations. Once informed of the additional requirements, however, the operator reconsidered and reluctantly put in a call to the engineering department to see what could be done. After the meeting, the facilitator said to me: “they didn’t understand the policy four years ago [when he first began as a facilitator], and they don’t understand it now.” The incentive to keep operations running had prevented the full resolution of a problem until the facilitator now intervened.

The influence of weak capabilities is apparent in Figure 3. Observe the link between “capability” and “problems encountered.” When the capability of the organization is low, the rate of problems encountered is higher. If the rate of problems

encountered exceeds the “capacity to resolve problems,” pressure is put on the organization to normalize deviance rather than correct problems. As a result, the improvement loop is less effective, and a gap begins to grow between the rule system and front line work.

Extending Decoupling: Front Line Deviance and Resistance

The model above includes two possible paths that problems may take: correction (improvement) and normalization. My observation of front line work, however, reveals a third outlet that is equally important when the volume of problems is high. I label this third path “active deviation.” Active deviation is distinct from normalization in an important way. When actors normalize deviance, they reclassify an act or condition as normal. In contrast, active deviation does not imply such reclassification. Actors know that they are breaking a rule and have no authority to amend the rule or make an exception. Actors also understand that if a similar situation recurs, the condition will remain deviant. Thus, active deviation does not form a balancing feedback loop in the manner that normalization does: while deviation allows actors to manage the flow of problems in the short run, the subsequent flow of problems is not reduced.

Active deviation is an important response in cases where rules are detailed and oversight is high. Referring to the model above, when the “scope of rules and strength of oversight” variable is high, the normalization loop is cut short. Actors who lack the capacity to resolve apparently minor problems by normalizing deviance may therefore choose to actively deviate instead.

Consider the example of the fan repair described above. When the fan shaft would not move, the mechanics faced several choices. They could correct the problem by stopping work and requesting a new job plan and risk assessment to cover additional tools - a step that would waste several man-hours of labor while the crew waited. Alternatively, they could deviate by improvising a solution. Given the magnitude of the risk, the improvised solution appeared acceptable; yet, the actors also knew that the rule requiring that all tools be listed on the job permit still stood. As one mechanic put it: “if you brought up every problem, you’d never get any work done at all.”

Conditions at Alpha combined to make deviance an attractive option on many occasions. First, the low state of capabilities and stretched planning process meant a plethora of minor problems on job permits and risk assessments. Second, the structure of the WCP process, combined with the degree of oversight from management, prevented actors from either resolving these problems or normalizing them. Even a simple revision to a job permit could entail significant delay due to the requirement for a new signature from a busy manager. Due to the volume and importance of maintenance work, managers and workers faced pressure not to incur such delays. At the same time, actors could not easily proceed without the revision. Workers feared job audits and talked about them often, even if in practice punishment was rare.

Minor problems on permits therefore put front line workers in a difficult situation.

An experienced member of the central WCP team summarized the problem:

“I think a lot of [the mechanics’] frustration comes from [the fact that] somebody else created this permit for them, and if exactly what they’re doing isn’t in the permit, do I stop, do I fix it – which is going to take another day – or do I just say the hell with it and move forward. That’s a bad position to put somebody in.” –
WCP Team Member

Placed in such difficult situations, front line workers at times resisted the process by deviating, as in the example above.

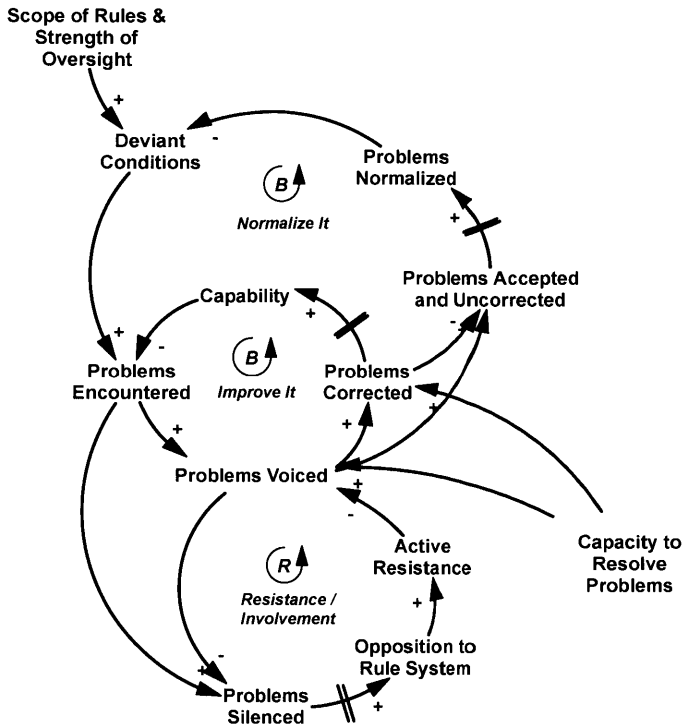


Figure 4: The Three Responses to Problems – Improvement, Normalization and Active Deviance

Figure 4 extends the model to illustrate active deviation and resistance. To do so, I introduce a new distinction between “problems voiced,” and “problems silenced.” When problems are voiced, they are managed through established organizational channels. Either the problem is corrected, or the problem is acknowledged and the actor is given permission to deviate. If the actor feels that a problem cannot be voiced, however, silencing becomes a form of active and unsanctioned deviance. Actors proceed

without reporting the problem and instead perform their own calculation regarding job risk.

Silencing forms an important *reinforcing* feedback loop. Acts of silencing put actors in an uncomfortable position, and build opposition to the WCP process. As a result, actors become less engaged in the process and become even less likely to voice problems. Actors in the planning and risk assessment stage silence problems by creating risk assessments that are deliberately vague and of low quality, allowing front line workers the flexibility to deviate later. In turn, front line actors stop reporting minor problems, preventing the corrective actions necessary to build an effective library for future use. As the gap between the rule system and practice grows, continued acts of silencing – especially against the backdrop of job audits and continued management pressure – only build further resistance.

The most prominent form of resistance was the behavior of actors with regard to job walkdowns. According to the WCP policy, unit operators and maintenance mechanics are required to have a discussion of job risks at the physical job location prior to the beginning of work. Walkdowns serve an important safety function: walkdowns allow actors to ensure that all controls listed on the risk assessment are in place, and also ensure that any changes to the job site in the days since the creation of the risk assessment are noted. In addition, walkdowns facilitate essential communication between unit operators and maintenance mechanics. Despite the benefits of walkdowns for the safety of work, however, on numerous occasions I observed operators at Alpha sign job permits in the operations shelter without visiting the job site with the mechanic. As one operator explained:

“If it’s a new guy, yeah, I’ll go out there to make sure he knows what he’s doing. But for these guys who’ve been working here for years, I’m not going to go tell them to wear gloves.” – Operator, Alpha (paraphrased from field notes)

This operator’s comment about “gloves” captures the sentiment of many on the front lines. To workers, the purpose of the WCP process is to police minor deviations and protect the company from lawsuits. Operators do not see walkdowns as an opportunity to find and correct errors, and so abstain from the practice. In turn, problems that might be uncovered through a full discussion at the job site are either not noticed or left unresolved.

The Physics of Improvement: Firefighting and Planning Breakdowns

Weak capabilities at Alpha at the time of implementation contributed to a steady stream of problems. Given the emphasis of management on the WCP process, why didn’t performance gradually improve?

Two additional reinforcing feedback loops help to explain why decoupling and resistance became so enduring. These loops are shown in Figure 5, and are labeled “Firefighting” and “Investment.” Both loops relate to physical processes over which the WCP process rests: the physical flow of paperwork planning activities, and the physics of plant infrastructure and reliability.

The loop labeled “firefighting” describes dynamics introduced by the structure of the WCP process. As described above, the WCP process introduces a much higher degree of planning and oversight into maintenance work. Whereas previously actors could complete risk assessments on the day of the job, now a risk assessment is

completed and reviewed as much as a week ahead of time. As a result, each maintenance job now passes through two distinct phases: a planning phase and an execution phase. As the examples above illustrate, high quality planning is essential to the effective functioning of the process. If job permits do not accurately describe the work, workers are put in uncomfortable situations and costly delays are introduced.

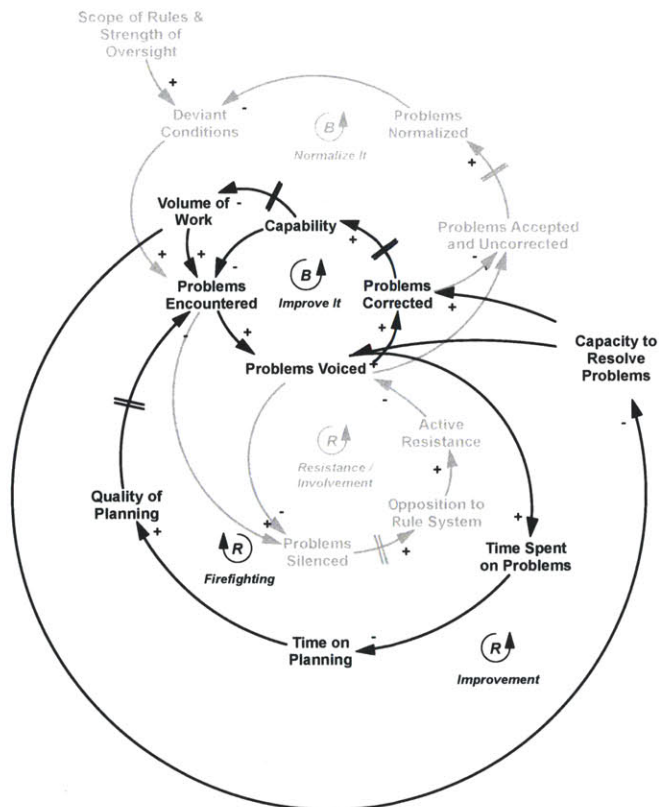


Figure 5: Firefighting and Crowding Out Improvement

Even worse, given limited planning resources, planning problems can be self-reinforcing. When job permits have errors, or when job scope changes, staff must devote time to correcting the most pressing work. Time on immediate tasks, however, takes time away from planning subsequent tasks, leading to still more problems in subsequent weeks. The dynamic is exacerbated by unit upsets and emergency break-in work. When

resources are stretched in the short-run, actors respond by reducing the quality of future planning work. For example, risk assessments are completed without visiting the job site, or without involving a mechanic with the right expertise. The continued poor quality of risk assessments drives the dynamics of resistance and decoupling.

A second reinforcing feedback loop involves the state of physical infrastructure. The rate of problems has several determinants: the quality of job planning, the number of conditions that are classified as deviant, and the absolute volume of work. The greater the volume of maintenance work that operators must manage on a given day, the more likely the operations staff is to encounter problems that must be resolved. The volume of maintenance work is itself endogenous and tied to the capability of the organization, as shown in Figure 5. Just as the act of correcting problems can improve the alignment between risk assessments and work, problems can also spur additional maintenance activities and infrastructure investments that prevent future breakdowns. When actors actively voice problems, small issues can be corrected before they cause expensive emergency work later.

Figure 5 illustrates this “investment” loop. Improvement (correcting problems) increases the capability of the organization, which reduces the future volume of work. When the workload is lower, operations managers now have more resources to devote to front line problem solving. Managers can be present in the field, and the delays necessary to correct and improve risk assessments become more manageable. In contrast, when the volume of work remains high, such problem solving is crowded out. Pressure to complete work puts pressure on the problem solving capacity of the organization, thereby driving the destructive dynamics of resistance and decoupling.

Tightening Control

Finally, the actions of managers in response to resistance and decoupling can further drive the dynamics. Figure 6 introduces two additional loops: “oversight,” and “tightening control.” When the incident rate is high, managers might respond by increasing oversight. In theory, such a response should prevent actors from normalizing deviance and thereby bring the incident rate back under control. (The balancing loop “oversight.”) However, when resources are stretched, increased oversight can have an additional effect. Oversight increases the volume of problems, causing actors to silence problems and resist the process, leading to still more incidents and still more oversight. “Tightening control” results in outcomes that are against the intentions of managers.

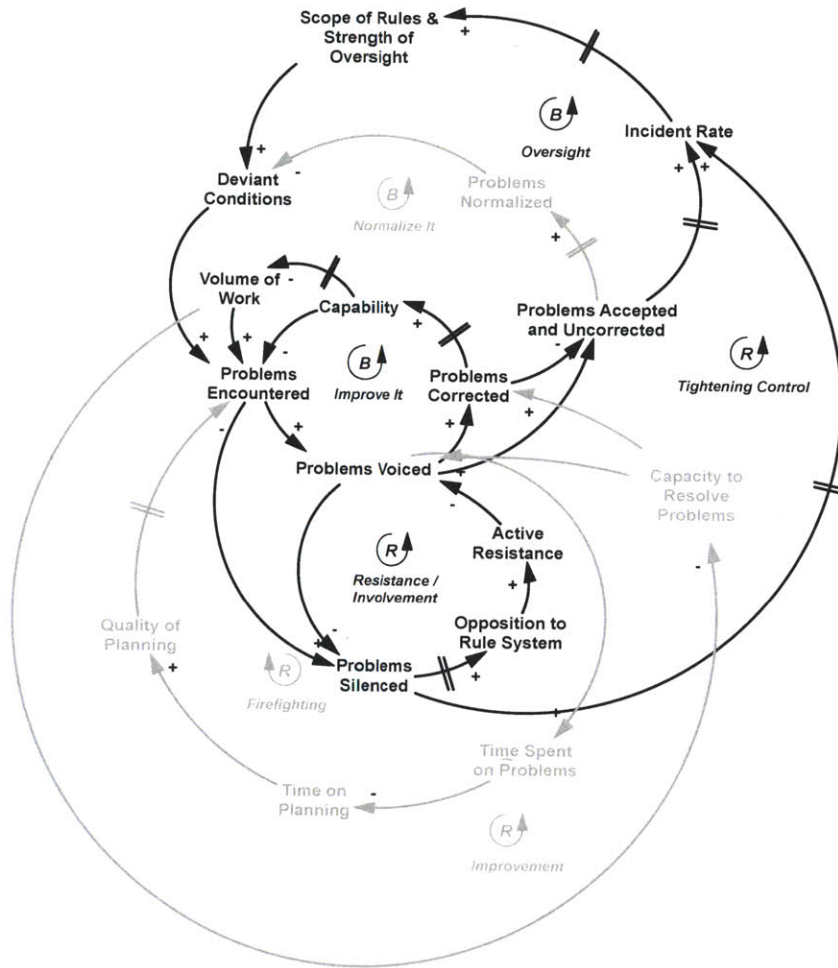


Figure 6: Tightening Control

Such dynamics were important in Alpha’s experience with the WCP process. During the early years of the WCP process, the incident rate remained high across the site. As a result, senior leaders faced pressure to improve results. Over the course of the WCP, senior leadership at Alpha embarked on a series of attempts to clarify rules, add detail, and increase oversight, as described in the case history. While such efforts did lead to the elevation and correction of some important problems in the short run, at times they also exacerbated the dynamics described above. Front line managers described a

process that was “continually changing,” creating new demands to learn how to correctly document risks and prepare job permits all while keeping up with work requirements.

An example helps to illustrate the impact of such changes on front line work. During a corporate audit in 2011, auditors discovered an abundance of temporary shelters in open areas around process units. These tents were used as staging areas for work or as break areas where workers could find shelter from the hot sun. However, such structures also introduced risk: it was best to have workers farther away from process units when not working inside them, so as to minimize injuries in the event of a fire or explosion. Leadership at Alpha was instructed to remove the structures, and the word spread down to the workforce. While the directive was clearly well intentioned, the change - like all others - introduced new “problems” that would require resources to resolve. The issue came up in a risk assessment that I observed. The job required welding together a very large metal piece, and lifting the piece up to attach it to a location inside a process unit. The group agreed that the safest way to do the work was to do the welding at ground level, and then lift the piece up using a crane. (The piece was too large to weld further away and transport.) Yet, doing so would require building a temporary enclosure to protect from the wind (standard practice for welding jobs). Workers had heard the new directive, and were annoyed: why were welding enclosures allowed above ground in the unit, but not at ground level? Would this new rule require them to do the welding in the unit, where the risks were greater? The workers were convinced that they could not build the enclosure, due to a fear of being audited. Thus, the new rule created a “problem” of interpretation that front line actors were forced to confront.

Gladly, on this occasion I observed a positive resolution to the problem, possibly due to the presence once again of a risk assessment facilitator from the central group. After returning from the job site to the operations shelter, the group conferred with several experts and came up with a solution: the welders could build a partial shelter that would protect them from wind, but would not be classified as an “enclosure,” per the new directive. Once again, compliance required effort and initiative to work across organizational boundaries. The solution created a new routine that would eliminate future problems. Unfortunately, while such outcomes were now common for higher risk work - due to efforts to build up and train the group of central risk assessment facilitators who participated in risk assessments for the highest risk jobs - units still lacked the resources to resolve the large volume of smaller problems in a similar manner.

In sum, the feedback structure shown above explains how a well-intentioned rule system can produce decoupling between rules and behavior. Top managers support rules and make strong efforts to enforce them. Workers, likewise, support the goal of improved safety and are directly impacted by the failure of the policy. Yet, when underlying capabilities are weak, detail and oversight only exposes problems and overwhelms the capacity of the organization to resolve those problems. Decoupling results as workers deviate and resist the process, as problems remain unresolved and continue to grow, and as managers attempt in vain to tighten control.

Successful Implementation at Beta: Building Worker Involvement

While the introduction of the WCP process at Alpha produced decoupling between rules and practice, the experience at Beta was different. Initially, Beta

experienced many of the same problems that Alpha experienced, including problems managing the flow of paperwork and resistance from the front lines. Over the course of the first year, however, the WCP process stabilized and began to support alignment between rules and practice. I argue that the stronger condition of underlying capabilities at Beta at the time of implementation was a major reason for the divergence in outcomes. Problems produced by the new process were fewer and were more easily managed. Moreover, the process of managing problems produced still stronger capabilities and, ultimately, still greater participation from the workforce. In essence, the vicious cycles that produced decoupling at Alpha became virtuous.

At the time that the full version of the WCP process was implemented at Beta, the state of all three capabilities was relatively strong, as described in the case history above. During the two years prior, Beta had substantially increased the size of its contract labor force in order to invest in infrastructure, and by 2010 had begun to scale back as the backlog of deferred maintenance declined. By late 2010, plant “availability” - a broad metric that reflects whether the plant is online or down for maintenance - was consistently in the 80% to 90% range. (In contrast, availability at Alpha when the full WCP process was introduced averaged in the 50%-60% range). The percentage of “rush emergency” workorders had steadily declined from 15-20% in 2007, to 5-10% in the first months of the initiative. (At Alpha, break-in work was in the 15-20% range at the equivalent point in time). Safety incident rates had also improved substantially. Communication between managers and workers had improved - in part due to the successful “near miss” program and due to efforts to complete major repairs that were a priority for the workforce. Finally, past conflicts between senior plant management and

middle management, and between operations and maintenance, had given way to a far more collaborative work environment.

Even in the context of a plant that was on a trajectory of improvement, however, the WCP process presented many of the same problems encountered at Alpha. In particular, Beta initially struggled to provide accurate and high quality job permits and risk assessments given the volume of work and detail required. One maintenance mechanic described a typical problem:

“[The planner] wrote it up as ‘replace the filters.’ Now, is that the filters on the fans, on the suction door, or on the motor? So it’s like, what filters? And when we addressed [the planners] on it, the attitude was, I’ve got 500 of these to do a day. I’m not going to write anything more than change filters down. Sorry. You’re going to have to figure it out. Well, that’s b.s.” – Company Mechanic, Beta

Although new staff positions were created specifically to create permits, these individuals occasionally lacked either the knowledge of equipment or the time to include relevant details such as the exact location of filters. (Recall that in the previous system, expert operators filled in these details at the job site). At times, errors had important implications: in this example, the omission meant that the operator had to shut down the pump for a job that did not require it. It is not so much the extra work that upsets the mechanic, however, than the unresponsiveness of the planning staff and his inability to see the problem resolved. The same feedback relationships once again apply - the need for detail and oversight (permits created by a separate planning staff) creates “problems” that are not resolved, causing actors to withdraw participation.

The more advanced status of Beta’s overall improvement initiative, however, gave the site several advantages in overcoming problems like these in the following

months. First, the stronger condition of infrastructure, knowledge, and relationships limited the volume of problems relative to Alpha and gave the site an advantage in resolving those that did arise. Fewer unit upsets and less reliance on reactive work meant that supervisors and managers could gradually devote more resources to following up on interpretation questions, process inefficiencies, and worker concerns. The groundwork that had been done to create consensus on some points of interpretation eliminated other potential problems. Because workers had already adopted many common routines to address job risks, the site could focus on the mechanics of the process without worrying about the content of rules at the same time. As one middle manager in a particularly successful unit put it:

"The [WCP] process has been easy for our operators to transition into because they were already fully engaged with the old [WCP] process... the bookkeeping, the walk downs, the task breakdowns and everything... our operators and supervisors understood it and followed [it]... So, when we transitioned, it wasn't a lot different than what the expectation was before." - Operations Manager, Beta

In contrast, a manager at Alpha explained the difficulties that he observed in his unit's first attempt to implement the process:

"The big learning has been - We missed the boat on setting the fundamentals. People got very inundated and focused on the paperwork, and on filling out boxes correctly, versus understanding the fundamentals. Now we are trying to go back and [teach people]... it's not about 10 page risk assessments, it's not about putting everything in. It's about really looking at the job, and putting in a control or mitigation [to reduce risk] that makes sense." - Operations Superintendent, Alpha

Building Involvement

Above all, managers at Beta could begin responding to worker concerns soon after the process was implemented. For example, in response to quality problems in the

planning stage (the above quote), knowledgeable craft mechanics were added to the planning staff to improve the quality of job plans, and the site made changes to the policy to allow front line workers more flexibility to make adjustments when errors were discovered. Unit managers began working with operators to resolve interpretation problems. As one manager explained:

"We get challenges from the operators. Believe me, it's not just me or a foreman saying [it]. The operators are pretty sharp, and they'll look at stuff, and [say]... we're not doing this one thing. And then we'll dig into it and we'll realize, you know what? We're not. And then we'll dig in [some more] and make sure it's true, and that message will get communicated to everyone." - Operations manager, Beta

In turn, front line workers began advocating for changes in a variety of manners. For example, when the personal gas monitors that workers wear on their clothes were activating frequently in one area of the plant, workers mounted a campaign to repeatedly file near misses until an infrastructure investment was made. On another occasion, workers who objected to the planned location of a new small structure used spray paint to paint on the ground "not here." (The structure would make access to important valves more cumbersome). Not all efforts were successful - and certainly grievances between management and the workforce remained - but on the whole, small successes in resolving problems encouraged workers to keep raising problems.

During my time in the field, I was impressed by the coordinated attention that site managers placed towards resolving some issues. One story in particular illustrates this phenomenon. The problem in question came up during an interview with an operator. This operator described to me a time when he had encountered a problem with a safety shower in his unit. For some reason, an alarm was activating indicating that the water in

the shower was hot. (“Safety showers” are installed at various locations so that a worker who is exposed to a hazardous chemical can quickly wash off with water). In his words:

“There’s a heat safety [alarm] on that safety shower. So if it gets too hot in there, the safety trips our alarm. So we’re just trying to get it fixed, trying to get it fixed. Well, nobody could find a problem with it. Nothing was wrong with it. And so we just went out and looked at it one day and, just looked at the temperature gauges inside the back door. And right before we’re getting ready to close it up, I was [thinking]... why is that 180 degrees? And I followed the [water line] back and there was cold water coming in. That’s not right.” - Operator, Beta

The operator discovered that the water line going into the safety shower had “steam tracing” running alongside it. Steam tracing is used during the wintertime to prevent the liquid inside lines from freezing. In the summer, however, the steam flow needs to be shut off to prevent the water from overheating. In this case, the hot water posed a safety hazard: had someone needed to use the safety shower in an emergency, they would have been burned by the hot water. The unit had a checklist of locations where tracing needed to be turned on or off, but somehow this one location was missed. I asked the operator why, and he explained that this one shower was the only shower with steam tracing - all of the others had been updated to use an electric tracing system that did not need to be shut off in the summer.

Even more impressive, however, was the manner in which this particular incident was handled across the plant. As the operator explained his discovery to me, I recalled hearing about this same discovery myself several weeks earlier while observing a meeting of unit superintendents. The operator had filed a “near-miss,” and the incident was picked up by the safety department and relayed to all of the unit superintendents in their Monday morning meeting. On Tuesday morning, while I was shadowing in a different unit on the other side of the plant, I heard the superintendent in that unit ask his

operators whether they knew of any safety showers with steam tracing. In fact, one operator answered immediately that two showers in this unit had the same issue. They would make note of them and put in a workorder to have them updated. Thus, a simple act by an operator to investigate a problem and raise an issue led to the elimination of several safety hazards across the plant. Note, however, the level of collaboration and attention required to fully act on the problem. The operator reported the problem, the safety department took notice, several superintendents followed up in their own units, and work orders were created - all for a relatively small problem that posed almost no immediate operational risk. Needless to say, when units are in upset or when work pressure on immediate tasks is high, attention to such details is easily overlooked. During the few upsets that I observed at Beta, the difference was palpable: attention switched almost entirely to the immediate task of bringing units back online, destroying momentum necessary to follow through on smaller issues.

Problems as Source of Participation

The general responsiveness of management to small issues carried through to the WCP process, and was apparent in my observation of front line work. In contrast to Alpha, where small problems in the course of work often put actors in a difficult position, the improved responsiveness of management at Beta alleviated some of this pressure. The difference is well captured by one episode that I observed between an operator, Tim, and two contractor maintenance mechanics, Mike and Dave (all names are pseudonyms) one morning at Beta:

After Tim finishes his morning rounds, I follow him back to the shelter where he greets Mike, the maintenance mechanic who will perform the fan preventive maintenance (PM) job that morning. Tim and Mike head out to the unit to inspect

the fan in question. Reaching this fan is a bit of a challenge; we must climb up a flight of stairs, walk along a raised walkway, and then climb a short ladder to reach the area where the fan unit is housed. There are three fan units under a low roof, each in a box about waist high and about 10 feet long by 4 feet wide. I stand aside while Tim and Mike have a discussion beside the middle fan. The problem that they are discussing is the fact that the number on the work order does not match the number on the fan. The two look at the paper several times, walk from one fan to the next, and try to determine whether they are looking for the numbers in the right places. Tim is sure that the middle fan is the fan that needs work, however, and suggests that they proceed with the verification. Mike remains by the fan while Tim and I climb back down to the ground level. We head over to a location on the ground level where there are five or six switches attached to a pole – all have chipped paint and show the effect of years of wear. Tim flips the switch that corresponds to the middle fan, and then walks over to a place where he can see Mike, who is still up above on the fan deck. Mike signals that the fan is still off, indicating that the power supply has been effectively cut. A circuit box 20 yards away – also one in a row of five or six - has been locked in the “off” position. Mike meets us on the ground, and together we look at the switches. The two now check the numbers on the switches, and determine that these also do not match - either to the work order or to the fan above. We walk over to the circuit breaker, where Tim again inspects to ensure that he has locked the correct one. He asks Mike whether he is comfortable proceeding, and the two agree to go ahead. As we are walking back, Tim explains that although he and Mike are somewhat uncomfortable that the numbers don't match, because they have physically verified the lockout he is comfortable allowing the work to proceed.

Tim and I arrive in the shelter; minutes later Mike also arrives, with another individual who will help him perform the work. Tim and Mike explain the situation to this third individual, Dave: although the numbers don't match, they suggest going ahead with the work anyway. Dave, however, objects. He explains that according to policy, at least two of the three numbers must match before they can proceed, and suggests taking the issue up with their maintenance supervisor. Mike and Dave then leave the shelter to follow up on the issue. It is now almost 10 am, more than an hour after the actual work was scheduled to begin.

Around 20 minutes later, Mike and Dave return. After talking with their supervisor, they suggest a more complete verification that the correct fan is locked out. We return to the unit, and this time, Tim removes the lock, restores power, and turns the fan on. Meanwhile, Mike and Dave stand above and verify that the fan is now running. The fan is then locked out once more, and Mike and Dave now verify that when the switch is activated, the fan remains off. All three are now satisfied that they have matched the correct circuit breaker with the correct switch and the correct fan, and that therefore the equipment is safe to work on. We return to the shelter, where paperwork can now be finalized. Together, the three men agree to each report the incident through both

maintenance and operations channels (Tim will report it as a “near miss”). Later in the morning, I observe as Tim informs one of the managers in his unit about the issue. This manager - an older individual who had worked in the unit for many years - nods and can recall a time when the fan was used for another purpose.

In this example, the operator and mechanic once again encounter a problem caused by the WCP process that cannot be resolved immediately. Initially, as in the example of the fan shaft at Alpha, the actors decide to resolve the problem by deviating. Because of his expert knowledge, the operator believes that he can safely make an exception to a standard rule, and the mechanic in turn trusts the operator's judgment. Although the operator expresses some discomfort with this outcome, deviating appears to be the best path forward. The actions of the second contractor, however, illustrate an alternate solution, made possible by management. First, the actors are comfortable raising the issue with their manager. Second, the maintenance manager is able to sanction a form of deviation: although the numbers are still misaligned, after an additional test, the actors are able to begin the work without any fear of acting inappropriately. More importantly, the actors are able to report the problem so that it is corrected in full later. The outcome leaves them engaged and more likely to raise similar problems in the future.

Returning to Figure 4, we see how this outcome resolves a crucial source of decoupling dynamics. Once again, latent defects both in infrastructure and knowledge (old number tags and a database that had not been updated) result in a problem. In this case, however, the problem results in a positive investment that builds the capability of the organization. Because the organization has the capacity to correct the problem - both in the short run by devising and sanctioning a safe work-around and in the long run by soliciting “near miss” reports and responding to underlying issues - the pressures that

cause actors to deviate in more dangerous ways are removed. By creating an outlet for a small, controlled amount of deviation in the short run (the “normalization” loop), the organization prevents active deviation and resistance (the “resistance” loop). As a result, the vicious “resistance” circle becomes virtuous: actors begin to believe in the effectiveness of the process, and become even more likely to raise issues rather than silence them.

The increased participation at Beta was evident in several forms. For one, actors were far more likely to participate in job walkdowns. The difference in walkdown behavior between the two plants is partly a function of the physical location of company mechanics at Beta: unlike at Alpha, company mechanics at Beta were not assigned to individual units and thus could not as easily collaborate with operators to resist the process. (At Beta, company mechanics were the most opposed to the change due to constraints imposed on their autonomy). Yet, even as many workers opposed some of the constraints imposed on them by the WCP process, their response often was to *increase* participation rather than withdraw participation. The fact that risk assessments occasionally contained errors was a reason to *participate* in walkdowns, rather than not. In fact, participation itself was a form of resistance: when management attempted to adjust the process to allow supervisors to perform some walkdowns, hourly workers insisted on performing them anyway. As one company mechanic explained:

“We have a lot of links in the chain. And there’s a lot of signatures on there. And you start to fall back, well, he signed it, so I think it’s good. And then you sign it. And you want to hope that the guy that signed it ahead of you didn’t think the same thing, well, I’ll sign it because the next guy will catch it. ... I like it when we work directly with the operators, walk to the job and talk to them about the job” -
Company Mechanic, Beta

Many operators, in turn, felt responsible for those working in their units and wanted to be sure that those individuals felt safe.

By participating in walkdowns, actors worked to support the WCP process. Table 5 compares common responses to problems that occurred during walkdowns across the two plants. Although the numbers are small, two points can be made. First, responses that preclude involvement, including active deviation and submitting to authority, were quite common at Alpha, but less so at Beta. (I code “submitting to authority” in cases where actors want to raise a problem, but are compelled not to). Second, several common responses at both plants support involvement and the WCP process. When actors engage in “explaining and correcting,” they are often enforcing a rule among peers or pointing out a problem that requires resolution. When actors engage in “discussion and joint interpretation,” they are working to apply the process in a particular context. The fan example above provides an example of both. At first, the mechanic explains the rule about number alignment to the others and corrects their earlier behavior; later, the group - with the participation of a manager - collaborates to develop a solution that allows them to deviate temporarily and complete the work. Finally, efforts to “challenge authority” can prevent short cuts or deviance on the part of supervisors or managers. All of these responses are necessary to correct problems and ensure that behaviors match standard practices for safe work.

Responses to Anomalies	Alpha	Beta
<i>Responses that Build Involvement</i>		
Explaining & Correcting	2	3
Discussion & Joint Interpretation	4	3
Challenging Authority	1	1
<i>Responses that Preclude Involvement</i>		

Disagreeing & Submitting to Authority	4	1
Active (Unsanctioned) Deviation	4	1
<i>Total Job Interactions</i>	43	18
<i>Total Anomalies Uncovered</i>	15	8
Percent Resolved by Involvement	47%	78%

Table 5: Responses to Anomalies

Loosening Control

In contrast to Alpha, Beta’s success in maintaining successful safety outcomes, in turn, meant that large-scale adjustments and changes to the process were not necessary. Recall the feedback loop “tightening control” in Figure 6, in which continued incidents at Alpha caused a series of attempts to increase oversight and improve the quality and detail of written risk assessments. Although written documentation of risks at Beta also suffered from poor quality - especially for low risk work - Beta did not face the same imperative to improve quality immediately. Front line workers were not subjected to job audits, and inconsistencies between units were resolved mostly by collaboration. The absence of audits, in turn, had an important influence on the opinions and actions of front line workers. Whereas workers at Alpha often talked about audits and the fear of being held accountable for problems that they believed were beyond their control, workers at Beta could instead focus on correcting and reporting problems of substance. Although workers at Beta might still deviate in potentially dangerous ways - as in the first part of the fan example above - at the same time workers and supervisors had more freedom to report problems, correct others, and engage in productive deviations like the second part of the example above. Returning to Figure 6, we see that once again important reinforcing loops work in the opposite direction: reduced oversight decreases the rate of

problems that require immediate attention (i.e. paperwork errors), but frees resources to invest in improvement, leading to more participation and ultimately the surfacing of productive problems in the future.

With a more engaged workforce, Beta could also devote more attention to educating workers to identify risks and follow certain standard practices. Building such knowledge was a major priority of site leadership. One remarkable episode during my time in the field underscored the merits of Beta's more participative approach. One morning, I was shadowing an operator who asked me: 'have you heard about the fire?' I had - a fire that had occurred about a year previously was the last major incident at Beta, and was often held up as an example of the importance of following and updating standard procedures. (No one was injured, but the fire caused expensive equipment damage and could have escalated to a far more serious event). The operator offered to show me the location of the fire, and I agreed. I was amazed to learn that this operator was the very same individual who had made the mistake that caused the fire. Now, a year later - despite the embarrassment that the incident must have caused him - he was offering, entirely unsolicited, to explain his mistake to me. The mistake occurred while he was isolating a pump from active flow so that a maintenance mechanic could change a filter the next day. After shutting the usual flow and running some lighter and cooler material through the pump to clean it out, the operator shut off all flows, waited a few minutes, and then opened a small bleed valve to let any remaining liquid escape. Unexpectedly, however, liquid continued to pour out of the small valve, indicating that a larger valve that he had shut was not holding. While he went to another part of the unit to

shut the flow off further upstream, this liquid continued to accumulate, until it touched up against a hot surface nearby and caught fire.

Although the failed valve was a contributing factor, the fire was caused in part by a mistake on the operator's part. All pumps have detailed step-by-step procedures for how to isolate and drain the pump for maintenance, including a list of which valves to turn in what order and at what time. For this pump, the procedure indicates that the operator must wait at least 15 minutes between flushing the pump and opening the bleed valve, so that any remaining liquid cools sufficiently. (This pump ordinarily pumped very hot material). On this occasion, however, the operator waited only 10 minutes, and the liquid that escaped remained hot enough to ignite. The operator explained that he had performed the task at least 15 times prior with no problem; yet, on this one occasion, the failed valve led to the event. In the subsequent incident investigation, more experienced operators reported that they always waited at least *an hour* to open the bleed valve, because they had been splashed in the past and knew how hot the liquid could be. The procedure reflected this knowledge, yet the operator had not followed it. Today, he and others had learned from the event and were more careful to look at procedures. The example illustrates not only how important standard procedures are for worker safety, but also how the more participative approach of management encouraged workers to use mistakes as an opportunity for learning. This approach to standard rules - already partly instilled at the time of roll-out - also supported the handling of problems introduced by the WCP process.

Taken together, Beta's approach to the WCP process, in the context of its overall improvement effort, produced relatively high coupling between safety rules and work

behaviors. Because underlying capabilities were stronger at the time of implementation, problems served as a catalyst for further improvement. As front line actors extended their participation, the link between rules and practice was continually renewed.

Discussion

The promise and peril of formal structure has tantalized organizational theorists for decades. Despite the appeal of bureaucratic control, why does formal structure so often appear to be no more than “myth & ceremony” (Meyer & Rowan 1977)? Certainly, bureaucracy imposes considerable limits on the autonomy of workers and can be a source of alienation and loss of dignity (Hodson 2001). Standard rules are also at times opposed to the demands of work and the interests of the organization. For these reasons, it is tempting to abandon bureaucracy as an ideal that can never be reached - a form that is fundamentally flawed and that organizations adopt only out of necessity. The case of workplace safety, however, provides a stark reminder of why many organizations continue to strive towards that ideal. Successful regulation of many modern technologies depends on organizations adopting standard approaches to risk. Psychological research tells us that individuals are notoriously bad at judging risk (Slovic 1987); in work contexts, given the repetitive nature of many work tasks, the complexity of interactions (Perrow 1984), the presence of time or other pressures, and the relative rarity of accidents, such judgements are only reinforced. Thus, for example, a worker may easily misjudge the risk of turning a valve too soon, of entering a confined space with a pipe running live process, or of improvising a solution that is not tested by engineers. Formal structure, in the form of specialized roles, written rules and procedures, and management oversight, counteracts these tendencies. Rules can be developed by experts based on

engineering analyses and on the accumulated knowledge of past accidents, and communicated to hundreds of actors across time and space. The consequences of failed adherence to rules can be deadly.

The very appeal of formal structure in the context of workplace safety, however, only sharpens the puzzle posed by its repeated failure, as in the case of Alpha. As I argue above, the most common explanations for the success and failure of rule systems in organizations are not helpful in distinguishing between Beta and Alpha. The two organizations employ the same technology, implemented an identical rule system, and began from a similar background of poor safety performance. Moreover, both faced considerable pressure from the corporate organization and from regulators to improve safety performance, and to a considerable degree were successful in that aim. The comparison between the two plants, then, presents a promising opportunity to advance theory on the phenomenon of decoupling in organizations.

I argue that a theory of decoupling must meet two requirements. First, it must locate decoupling in the individual decisions by front line actors to deviate from rules. Second, such a theory must be dynamic. By tracing the evolution of a rule system in two similar organizations, I provide a theory that accounts for the promise of formal structure while also explaining why that promise is so elusive. The central tension, I show, stems from the inflexibility that formal structure creates. Standard rules and management oversight reduce the discretion of front line actors to respond to problems in the moment, and thus impose coordination costs on organizations. When “problems” occur, managers must be consulted, meetings arranged, interpretation issues resolved, and errors in paperwork corrected. The success of rule systems, in part, depends on the ability of

organizations to resolve such problems. Existing accounts emphasize the inherent limits of organizations' ability to resolve such problems, and the fact that in order to function, organizations must allow some discretion (e.g. Lipsky 1980). Yet, even if organizational action can never be entirely formalized, a central insight of my analysis is that the success of formal structure is *variable*, and can evolve over time as organizations change in their ability to resolve the flow of problems that emerge.

How do organizations differ in their ability to process problems? While organizations can attempt to increase their capacity to resolve problems by adding resources or slowing work, given the pressures of most work environments, such strategies are limited. Instead, I argue that the success of formal structure depends on reducing the rate at which problems are *created*. In my analysis of problems encountered at Alpha and Beta, I find that most problems have underlying causes that can be reduced over time through investment in infrastructure, knowledge, and social relationships. Such efforts, however, require sustained investment from management and support for the initiative of front line actors to develop pragmatic methods of compliance (Huisin & Silbey 2011). At times - as in the example of the misaligned numbers - organizations must relax slightly the requirements of formal structure so as to maintain the participation of front line actors and encourage the development of capabilities that increase compliance in the future. In so doing, organizations once again maintain the rate of problems at a level that is within the capacity of the organization to resolve those problems in constructive ways. In contrast, efforts to impose formal structure when underlying capabilities are lacking may elevate the rate of problems to unsustainable levels, putting front line actors into situations where active deviation appears necessary.

Participation gives way to resistance and rules become increasingly decoupled from practice.

A dynamic view of problem resolution in organizations provides new insight into the pronounced effects of the external environment on organizations. When organizations are compelled to demonstrate strict compliance in the short run, unless capabilities are already well developed, the very efforts necessary to develop sustained compliance in the long run are cut short. The comparison between Beta and Alpha illustrates this point. While Beta had more leeway to develop capabilities prior to the implementation of the full WCP process, Alpha faced strong pressure to conform throughout. Thus, the imperative to conform to norms of bureaucratic rationality can be a source of decoupling, *even* in contexts where rules are effective and where organizational actors support their implementation. More specifically, this finding helps to explain the failed attempts of so many organizations to adopt the principles of the quality movement, even given the successes of many of the earliest adopters (Westphal et al 1997, Zbaracki 1998, Repenning & Sterman 2002).

These results have important implications for the regulation of risk, both internally and by the state. In recent years, analysts in the news media and in the public policy arena have bemoaned the failure of regulatory action and public pressure to prevent several large scale organizational disasters, especially by repeat offenders. In a large-scale quantitative study of corporate self-regulation in the area of environmental performance, Short & Toffel (2010) show that the worst performers very often fail to make progress on commitments to self-regulate. To some, such repeated failures are viewed as evidence of the “amoral calculator” view of organizations (Kagan & Scholz

1984), in which organizations deliberately choose to violate regulations when the benefits outweigh the costs. The continued failure of regulation has led to calls for even stricter penalties for non-compliance, including criminal liability for the leaders of such organizations.

While such calls may have merit in some circumstances, the results here show the limits of regulation based on deterrence. Because the worst performers often have the weakest capabilities, they are most vulnerable to fall into the trap described above. Such organizations may require years of investment in infrastructure and human capital before full compliance is truly achievable. In such cases, pressures to improve too quickly may produce dynamics that undermine improvement efforts. At the same time, when regulatory pressure is too weak, poor performers may forego investment in improvement altogether. Successful regulation, then, requires navigating a difficult balance - a balance that can easily come unhinged.

More broadly, these dynamics illustrate how external pressure can act as a source of sustainable competitive advantage. In many contexts, the ability to perform complex tasks reliably can be a substantial competitive advantage (Hannan & Freeman 1984). Bureaucratic control, when effective, can produce reliable outcomes while also increasing transparency into how outcomes are produced. Research in the strategy literature has long sought to understand why the attributes that make some organizations successful are not easily imitated by others. The concept of capabilities is often invoked as an explanation for such advantage. The above analysis provides insight into precisely how capabilities are developed, how they are linked to competitive outcomes, and why they are so difficult to reproduce.

Finally, these findings suggest several avenues for future research. First, research might consider in more detail the conditions that are necessary to achieve success. How might Beta's experience be translated into broader strategies for both government regulation and industry self-regulation? Are there ways for both senior managers and regulators to encourage investment in the right areas and support front line involvement? Second, research might consider settings where work is less routine or where interests are not so clearly aligned. When deviations from rules are more often necessary or where the pace of technological change is faster, can bureaucratic control still succeed? Finally, given the emphasis on consensus in the above analysis, how can organizations also encourage dissent so as to continually challenge assumptions and uncover problems before they become accidents? Although the rise of the audit society (Power 1997) undoubtedly contains much symbolism and cannot replace strong government regulation, there remains much to like in the bureaucratic form of organization.

References

- Adler, P. S, and B. Borys. 1996. "Two types of Bureaucracy: Enabling and Coercive." *Administrative Science Quarterly* 41(1):61–89.
- Adler, Paul. 1993. "The 'learning bureaucracy': New United Motors Manufacturing Incorporated." Pp. 111–94 in *Research in Organizational Behavior*, vol. 15, edited by Barry Staw and Larry Cummings. Greenwich, Conn: JAI Press.
- Azoulay, P., N. P. Repping, and E. W. Zuckerman. 2010. "Nasty, Brutish, and Short: Embeddedness Failure in the Pharmaceutical Industry." *Administrative Science Quarterly* 55(3):472–507.
- Beamish, T. D. 2000. "Accumulating trouble: Complex Organization, a Culture of Silence, and a Secret Spill." *Social Problems* 47(4):473–498.
- Bechky, B. A. 2003. "Sharing meaning across occupational communities: The transformation of understanding on a production floor." *Organization Science* 14(3):312–330.
- Brown, John Seely, and Paul Duguid. 1991. "Organizational Learning and Communities-of-Practice: Toward a Unified View of Working, Learning, and Innovation." *Organization Science* 2(1):40–57. Retrieved September 9, 2009.
- Burawoy, M. 1982. *Manufacturing consent: Changes in the Labor Process under Monopoly Capitalism*. Chicago, IL: University Of Chicago Press.
- Canales, R. 2011. "Rule bending, sociological citizenship, and organizational contestation in microfinance." *Regulation & Governance* 5(1):90–117.
- Carlile, P. R. 2002. "A pragmatic view of knowledge and boundaries: boundary objects in new product development." *Organization Science* 13(4):442–455.
- Carroll, J. S, J. W Rudolph, and S. Hatakenaka. 2002. "Learning from experience in high-hazard organizations." *Research in Organizational Behavior* 24:87–137.
- Carroll, J. S, J. Sterman, and A. Marcus. 1997. "Playing the maintenance game: How mental models drive organizational decisions." in *Debating Rationality: Nonrational Aspects of Organizational Decision Making*, edited by R Stern and J Halpern. Ithaca: Cornell University Press.
- Coglianesi, C., and J. Nash. 2001. *Regulating from the inside: can environmental management systems achieve policy goals?* Washington, DC: Resources for the Future.

- Dierickx, I., and K. Cool. 1989. "Asset stock accumulation and sustainability of competitive advantage." *Management Science* 35(12):1504–1511.
- Dobbin, F. 2009. *Inventing Equal Opportunity*. Princeton, NJ: Princeton Univ Press.
- Edelman, L. B. 1992. "Legal ambiguity and symbolic structures: Organizational mediation of civil rights law." *The American Journal of Sociology* 97(6):1531–1576.
- Edelman, L.B., H.S. Erlanger, and J. Lande. 1993. "Internal dispute resolution: The transformation of civil rights in the workplace." *Law and Society Review* 27(3):497–534.
- Edmondson, A.C., and A.L. Tucker. 2003. "Why Hospitals Don't Learn from Failures: Organizational and Psychological Dynamics that Inhibit System Change." *California Management Review* 45(2):55–72.
- Eldridge, J.E.T. 1968. *Industrial disputes: Essays in the sociology of industrial relations*. London: Routledge & K. Paul.
- Freeland, R. F. 2001. *The struggle for control of the modern corporation: Organizational change at General Motors, 1924-1970*. Cambridge: Cambridge University Press.
- Glaser, B. G, and A. L Strauss. 1967. *The discovery of grounded theory: Strategies for qualitative research*. New Brunswick, NJ: Aldine Transaction.
- Gouldner, A. W. 1954. *Patterns of Industrial Bureaucracy*. New York, NY: Free Press.
- Gunningham, N., R. A. Kagan, and D. Thornton. 2003. *Shades of green: business, regulation, and environment*. Palo Alto, CA: Stanford University Press.
- Hackman, J. R., and R. Wageman. 1995. "Total quality management: Empirical, conceptual, and practical issues." *Administrative Science Quarterly* 40(2):309–342.
- Hall, A. 1993. "The corporate construction of occupational health and safety: A labour process analysis." *The Canadian Journal of Sociology* 18(1):1–20.
- Hallett, T. 2010. "The myth incarnate." *American Sociological Review* 75(1):52–74.
- Hannan, M. T., and J. Freeman. 1984. "Structural inertia and organizational change." *American Sociological Review* 49(2):149–164.
- Haynes, A.B. et al. 2009. "A surgical safety checklist to reduce morbidity and mortality in a global population." *New England Journal of Medicine* 360(5):491–499.
- Heimer, C. A. 1992. "Doing your job and helping your friends: Universalistic norms about obligations to particular others in networks." Pp. 143–164 in, edited by N Nohria and R.G. Eccles. Boston, MA: Harvard Business School Press.
- Hodson, R. 2001. *Dignity at Work*. Cambridge: Cambridge University Press.

- Huising, R., and S. S. Silbey. 2011. "Governing the gap: Forging safe science through relational regulation." *Regulation & Governance* 5(1):14–42.
- Kagan, R. A., and J. T. Scholz. 1984. "The criminology of the corporation and regulatory enforcement strategies." Pp. 69–74 in *Enforcing Regulation*, edited by K. Hawkins and J. Thomas. Boston: Kluwer-Nijhof.
- Kalev, A., E. Kelly, and F. Dobbin. 2006. "Best practices or best guesses? Assessing the efficacy of corporate affirmative action and diversity policies." *American Sociological Review* 71(4):589–617.
- Katz, D. 1964. "The motivational basis of organizational behavior." *Behavioral Science* 9(2):131–146.
- Kellogg, K. C. 2009. "Operating room: relational spaces and microinstitutional change in surgery." *American Journal of Sociology* 115(3):657.
- Kelly, E.L., and F. Dobbin. 2007. "How to stop harassment: Professional construction of legal compliance in organizations." *American Journal of Sociology* 112(4):1203–1243.
- Kunda, G. 1992. *Engineering culture: Control and commitment in a high-tech organization*. Philadelphia, PA: Temple University Press.
- Lipsky, M. 1980. *Street-level bureaucracy: Dilemmas of the Individual in Public Service*. New York: Russell Sage Foundation Publications.
- March, J. G., M. Schulz, and X. Zhou. 2000. *The dynamics of rules: Change in written organizational codes*. Palo Alto, CA: Stanford University Press.
- March, J. G., and H. A. Simon. 1958. *Organizations*. Oxford, England: Wiley.
- Meyer, J. W., and B. Rowan. 1977. "Institutionalized organizations: Formal structure as myth and ceremony." *The American Journal of Sociology* 83(2):340–363.
- Morrill, C., M. N. Zald, and H. Rao. 2003. "Covert Political Conflict in Organizations: Challenges from Below." *Annual Review of Sociology* 29:391–415.
- Orr, J. E. 1996. *Talking about machines: An ethnography of a modern job*. Cornell University Press.
- Perrow, C. 1986. *Complex organizations: A critical essay*. 3rd ed. New York, NY: Random House.
- Perrow, Charles. 1999. *Normal accidents: Living with high-risk technologies*. Princeton, NJ: Princeton University Press.

- Pires, R. 2011. "Beyond the fear of discretion: Flexibility, performance, and accountability in the management of regulatory bureaucracies." *Regulation & Governance* 5(1).
- Power, M. 1997. *The Audit Society: Rituals of Verification*. Oxford: Oxford University Press.
- Rees, J. V. 1988. *Reforming the workplace: A study of self-regulation in occupational safety*. Philadelphia: University of Pennsylvania Press.
- Reid, D. 1981. "The role of mine safety in the development of working-class consciousness and organization: The case of the Aubin Coal Basin, 1867-1914." *French Historical Studies* 12(1):98–119.
- Repenning, N. P, and J. D Sterman. 2002. "Capability traps and self-confirming attribution errors in the dynamics of process improvement." *Administrative Science Quarterly* 47(2):265–295.
- Repenning, N. P. 2001. "Understanding fire fighting in new product development*." *Journal of Product Innovation Management* 18(5):285–300.
- Sastry, M. A. 1997. "Problems and paradoxes in a model of punctuated organizational change." *Administrative Science Quarterly* 42(2):237–275.
- Schreyögg, G., and M. Kliesch-Eberl. 2007. "How dynamic can organizational capabilities be? Towards a dual-process model of capability dynamization." *Strategic Management Journal* 28(9):913–933.
- Scott, W. R., and J. W. Meyer. 1983. "The organization of societal sectors." Pp. 129–54 in *Organizational Environments: Ritual and Rationality*, edited by J.W. Meyer and W.R. Scott. Newbury Park, CA: Sage.
- Scott, W.R. 2003. *Organizations: Rational, natural, and open systems*. Englewood Cliffs, NJ: Prentice Hall.
- Selznick, P. 1948. "Foundations of the Theory of Organization." *American Sociological Review* 13(1):25–35.
- Short, J. L, and M. W Toffel. 2010. "Making self-regulation more than merely symbolic: The critical role of the legal environment." *Administrative Science Quarterly* 55(3):361–369.
- Silbey, S. S. 2009. "Taming Prometheus: Talk about Safety and Culture." *Annual Review of Sociology* 35.
- Slovic, P. 1987. "Perception of risk." *Science* 236(4799):280–285.

- Snook, S. A. 2002. *Friendly fire: The accidental shutdown of US black hawks over northern Iraq*. Princeton, NJ: Princeton University Press.
- Spear, S., and H. K. Bowen. 1999. "Decoding the DNA of the Toyota production system." *Harvard Business Review* 77:96–108.
- Spear, S. J. 2009. *Chasing the Rabbit: How market leaders outdistance the competition and how great companies can catch up and win*. New York, NY: McGraw-Hill.
- Starbuck, W.H. 2009. "Cognitive reactions to rare events: Perceptions, uncertainty, and learning." *Organization science* 20(5):925–937.
- Teece, D. J., G. Pisano, and A. Shuen. 1997. "Dynamic capabilities and strategic management." *Strategic Management Journal* 18(7):509–533.
- Tucker, A. L, A. C Edmondson, and S. Spear. 2002. "When problem solving prevents organizational learning." *Journal of Organizational Change Management* 15(2):122–137.
- Vallas, S. P. 2003. "Why teamwork fails: Obstacles to workplace change in four manufacturing plants." *American Sociological Review* 68(2):223–250.
- Vaughan, D. 2005. "Organizational rituals of risk and error." Pp. 33–66 in *Organizational encounters with risk*, edited by B Hutter and M.K. Power. Cambridge, UK: Cambridge University Press.
- Vaughan, D. 1996. *The Challenger launch decision: Risky technology, culture, and deviance at NASA*. Chicago, IL: University of Chicago Press.
- Vaughan, D. 1999. "The dark side of organizations: Mistake, misconduct, and disaster." *Annual Review of Sociology* 25(1):271–305.
- Weick, K. E, K. M Sutcliffe, and D. Obstfeld. 1999. "Organizing for High Reliability: Processes of Collective Mindfulness." Pp. 81–123 in *Research in Organizational Behavior*, vol. 1, edited by R. S Sutton and B.M. Staw. Stanford: Jai Press.
- Weick, K. E. 1976. "Educational Organizations as Loosely Coupled Systems." *Administrative Science Quarterly* 21(1):1–19.
- Westphal, J. D, R. Gulati, and S. M Shortell. 1997. "Customization or conformity? An institutional and network perspective on the content and consequences of TQM adoption." *Administrative Science Quarterly* 42(2).
- Zbaracki, M. J. 1998. "The Rhetoric and Reality of Total Quality Management." *Administrative Science Quarterly* 43(3):602–605.

Essay 3 – Giving up Too Soon: The Failure of Win-Win Investments in Process Improvement and Industry Self-Regulation

Abstract

In recent years a growing stream of research has sought to identify how the actions of managers can influence compliance with regulation and corporate social responsibility in areas such as environmental performance, workplace safety, and financial accounting. One such strategy that has received widespread attention is the search for proactive “win-win” investments that improve both regulated outcomes and the bottom line. Yet, the prevalence of win-win investments raises an important question: if proactive investments are really profitable, why are they so often not performed, especially when their existence is so widely acknowledged? To develop insight into this question, we develop a detailed simulation model of a proactive investment in building maintenance and energy use. While a proactive investment can produce substantial positive returns, we illustrate why achieving full returns can be so difficult. Specifically, even when managers make substantial proactive investments, investments may not be large enough or long enough to cross a tipping threshold. In such cases, despite the appearance of success in the short-term, performance gradually erodes to its original state, wiping out gains. Thus, successful self-regulation and process improvement depends not only on managers recognizing and acting on opportunities, but also on managers understanding tipping dynamics and sustaining investments beyond levels that might initially appear sufficient.

Introduction

In recent years a growing stream of research has sought to identify how the actions of managers can influence compliance with regulation in areas such as environmental performance, workplace safety, product quality, and financial accounting. A number of scholars have argued that organizations can outperform peers and develop substantial competitive advantage by adopting specific strategies of self-regulation (Hart 1995, Coglianesse & Nash 2001, Parker 2002, Estlund 2010). One such strategy that has received widespread attention is the search for “win-win” investments that improve both regulated outcomes *and* the bottom line (Porter & Lind 1995, Christmann 2000, Gunningham et al. 2003). Examples of win-wins abound in both the academic and policy literatures and in the popular press. For example, numerous studies document the existence of energy-saving or pollution-reducing technologies with positive net present value, short payback times and high ROI (e.g. Hawken, Lovins & Lovins 1999; Creyts et al. 2007). In the area of health and safety, targeted investments in technology and infrastructure can reduce accidents as well as costs associated with breakdowns and poor reliability. Given such promise, identifying win-win investments and convincing organizations to make them has become an important strategy of individuals and organizations associated with the sustainability and environmental movements (Charles, 2009).

While there is widespread agreement that win-win investments are real, surprisingly, organizations very often fail to make them. Consider the case of routine maintenance of buildings and physical infrastructure. Studies show that simple commissioning of building systems can generate substantial energy savings with payback

periods on the order of a few years (e.g. Effinger et al., 2009). Problems with temperature control systems, dampers that fail to adequately mix outside air, pipe and duct leaks, failed steam traps, and worn equipment can each introduce costly inefficiencies, reduce occupant comfort, and pose safety hazards. Moreover, investment in energy efficiency would contribute significantly to the cause of reduced greenhouse gas emissions. Buildings account for between 20 and 40% of US energy consumption, and are recognized as a major source of untapped potential in the effort to reduce emissions (e.g. TIAX 2005, Perez-Lombard et al. 2008, Martani et al. 2012, Heo et al. 2012).

Neglected win-win opportunities extend to other areas of infrastructure investment and process improvement. For example, in the case of the US electrical grid, Amin (2011) estimates that investment in infrastructure would more than pay for itself in the form of reduced outage costs and improved reliability. Yet, while the benefits of “preventive” and “predictive” maintenance are preached by almost every maintenance organization and textbook (e.g. Levitt 2009), organizations instead too often choose to tolerate expensive and repeated failures and breakdowns.

Why are such promising investment opportunities so often left on the table? A large literature in economics, psychology, and organization theory provides several possible explanations. First, some economists argue that underinvestment reflects an overoptimistic view of the value of investments by analysts (Gillingham et al. 2009). For example, analysts may neglect hidden costs such as the reduction in quality that an investment, such as an energy efficient technology, might bring (Jaffe et al. 2004), or costs associated with uncertainty in returns (Sutherland 1991). According to the rational

actor model, win-win investments must not exist because a rational actor would have already made them.

A second set of explanations acknowledges the existence of win-win investments and instead attributes underinvestment to market failures or behavioral departures from rationality. Market failures may come in several forms. Actors may lack access to the credit necessary to finance up-front investments. Principal-agent or asymmetric information problems may arise when actors making investments do not directly realize savings, or when sellers of a technology cannot credibly communicate future (unobservable) benefits (Howarth & Sanstad 1995). For example, a property owner might face difficulty passing on the costs of an investment to a tenant, and so underinvest (Jaffe & Stavins 1994). Lastly, literature in behavioral economics identifies several biases that may influence investment decisions. For example, individuals consistently overemphasize short-term costs and underemphasize longer-term gains that are less “salient” (Yates & Aronson 1983).

Finally, organization theory provides several explanations for underinvestment at the organizational level of analysis. First, the structure of organizations often impedes awareness of investment opportunities. Actors often work within functional boundaries and face narrow goals that fail to capture the full set of opportunities for learning and improvement (Cyert & March 1963). Second, organizations often face added market and stakeholder pressures to prioritize short-term results over longer-term investment (Repenning & Henderson 2010).

While these explanations for under-investment are compelling, they are only partly satisfactory for the case of many large win-win opportunities. Certainly, principal-

agent problems, information asymmetries, management biases and short-termism can influence investment decisions in organizations. Yet, such influences are not always active. Many investment opportunities *are* widely recognized for the positive returns that they provide, yet still are not achieved by many organizations that try. Senior leaders have the authority and access to credit to make investments with delayed payoff, and routinely do so. For example, organizations make investments in infrastructure, technology and process improvement all the time, yet only some achieve the highest levels of reliability and associated benefits that such investments can provide (Repenning & Sterman 2002). How do we explain failure in such cases?

We argue that to understand the performance of win-win investments, we must look beyond the initial investment decision to the dynamics of how investments unfold over time. To do so, we develop a detailed simulation model of a proactive investment in building maintenance at a large research university. The model confirms that a proactive investment would reduce energy use, increase reliability, *and* generate a positive return on investment. At the same time, our case study yields important insights into why such an outcome might easily fail to materialize.

Specifically, we find that the presence of tipping dynamics can have a large influence on investment outcomes. Even where managers make large initial investments, if investments are not large enough or long enough to cross a tipping threshold, performance will begin to gradually erode, wiping out gains. Moreover, in the short run, the difference between successful and unsuccessful investments can be difficult for managers to discern. Thus, managers facing short-term pressures may easily underinvest, even when investments are supported and resources are available. Successful self-

regulation and process improvement, then, depends not only on managers recognizing and acting on opportunities, but also on managers understanding tipping dynamics and sustaining investments beyond levels that might initially appear sufficient.

Research Setting & Methods

To understand the dynamics of a proactive win-win investment, we study the case of building maintenance at MIT, a large research university. For several reasons, building maintenance is an excellent setting to study possible alignment between regulated outcomes, social responsibility, and the bottom line. First, building maintenance is an area where clear best practices are known to improve reliability and ultimately profitability (e.g. Moubrey 1997, Levitt 2009). By investing in preventive maintenance and infrastructure renewal, organizations can prevent unplanned breakdowns and associated costs. These costs include disruptions to normal operations, collateral damage, inefficiencies due to a decreased ability to plan and schedule work, costs of breakdowns caused by rushed work or poor quality parts, damage to reputation, top management turnover and costs of enhanced regulatory oversight.

At the same time, investment in routine maintenance promises substantial benefits from the standpoint of regulated outcomes and social responsibility. As described in the introduction, buildings account for a substantial fraction of US energy usage, and present a large opportunity to reduce greenhouse gas emissions. In addition, improved maintenance eliminates safety hazards, both for building occupants and for workers (e.g. Reason 1997). To give just one example, several years ago at MIT a problem with an expansion joint in a high-pressure steam pipe caused an explosion inside a building,

creating the potential for serious injury (luckily, no one was present at the time). The event caused more than a million dollars in damage – many times the organization’s entire annual maintenance budget, and might have been prevented by a simple inspection and part replacement.

MIT is especially well positioned to gain from an investment in routine maintenance. Due to the aging of campus buildings and past underinvestment in maintenance, by 2005 – the start of the time period for this study – the university faced a deferred maintenance backlog of more than one billion dollars. The poor condition of buildings, in turn, was responsible for a maintenance organization that was highly reactive. More than 90% of maintenance work orders between 2005 and 2007 were responses to customer calls reporting problems or breakdowns. In interviews, maintenance supervisors reflected on the inefficiencies introduced by such a reliance on reactive work. In particular, the need to constantly attend to customer needs prevented allocating resources to preventive work that could reduce the risk of future expensive breakdowns, like the steam pipe explosion described above. As one supervisor explained:

“You know, we’re a customer service organization. It’s almost like we’re afraid to commit completely to the behind the scenes stuff, because we want to get to the visible stuff so quickly. That’s not spoken, but I think that’s – having the resources available – the customer doesn’t care if a belt is flapping in a fan. It might not matter for a year down the road, but to us it might be in January in the middle of the night that the fan shuts down – to us it’s important, but to the customer it’s not, so our resources go to what the customer wants, for the most part.” – *Facilities employee*

By not replacing a fan belt today, the organization risks a far more expensive breakdown later. The reliance on reactive work also hindered efforts to plan and schedule work:

“It’s a fire drill... it’s who’s screaming right now. So your priorities change on an hourly basis, probably a half-hourly basis during the day, and it’s kind of – it’s basically a constant fire drill. [So you] kind of have a tendency to leave it once you get to a point where no one is complaining.” – *Facilities employee*

Due to the state of the maintenance organization, this university especially stood to achieve substantial gains from an investment in routine maintenance. The potential gains due to reduced energy consumption were also clear. A large fraction of customer calls are “hot and cold calls,” reflecting HVAC systems out of adjustment and in need of repair.

Methods

The strong potential for a successful win-win investment in routine maintenance makes MIT an ideal setting to study the dynamics of such an investment. To do so, we construct a simulation model of MIT’s maintenance organization and parameterize it using several data sources. The model offers several advantages over existing approaches to the analysis of proactive investments.

First, the model allows us to consider the technology of an investment together with the organizational context. Many analyses of green investments consider costs and savings from an engineering or technical standpoint; our analysis integrates the physics and economics of the plant with realistic behavioral decision rules that govern plant system dynamics. Specifically, the model captures the ongoing tradeoffs that actors face between reactive customer service work and the proactive work necessary to achieve both environmental and efficiency goals.

Second, a simulation model allows us to experiment with and compare many different policies for proactive investment over time. Too often, proactive investments

are treated as discrete events that either produce or fail to produce a positive return on investment. In this analysis, we extend these analyses to consider a complex organizational initiative in which managers face a variety of choice that can influence outcomes.

The model is constructed using the system dynamics method (Sterman 2000). System dynamics is widely used to model the dynamics of complex feedback systems, including organizations (e.g. Sterman et al. 1997; Sastry 1997; Oliva & Sterman 2001; Repenning & Sterman 2002; Morecroft 2007; Carroll, Morrison & Rudolph 2009; Freeman, Larsen & Lomi 2012). To create a model of a maintenance organization, we build on existing models of service delivery operations (Oliva & Sterman 2001), and case studies of maintenance organizations (Carroll et al. 1997, Sterman 2000 pp. 66-79).

The model is parameterized using several data sources. First, to capture the decision rules of the front line maintenance organization and determine parameters for productivity and cost, we use maintenance work order data from the university's SAP system, from 2005 to 2008. The data captures worker productivity (work orders/hour), total hours worked, and the allocation of time between reactive and proactive work. Second, to model the state of the physical plant and the creation of work orders, we draw on a detailed engineering assessment of building systems completed in 2007. The assessment contains a database documenting every building system, categorized by type (HVAC, electrical, envelope, etc.), campus building, renewal year, and estimated renewal cost. Third, we construct a model of building energy usage based on actual energy consumption, by building and type (chilled water, steam, and electrical), between 2000 and 2006. Finally, to gain more insight into organizational decision-making processes,

we conducted interviews with more than thirty individuals, from maintenance hourly workers to senior administrators, between 2007 and 2008.

In the following section, we describe in more detail how the various data sources are triangulated into a model of the maintenance organization. Then, we use the model to analyze the dynamics of a proactive investment in routine maintenance.

A Model of Building Maintenance & Energy Usage

Maintenance Staffing & Work Orders

We start by formulating and calibrating a model to match the time series data on proactive and reactive maintenance work orders. We form the core of the model by adapting the structure developed by Sterman (2000) and Oliva & Sterman (2001), shown below in Figure 1. The causal loop diagramming convention is used to provide an overview of the main relationships; these diagrams capture the essential feedback structure of the model for presentation purposes, but are not intended to present the full model at the level of equations. The appendix presents full model documentation, including detailed model structure diagrams, full equations, and related documentation needed to replicate the analysis presented here.

Work orders are opened and accumulated in a backlog until they are closed. Two kinds of work orders are considered: reactive maintenance work orders and proactive (planned) maintenance work orders. Reactive work orders are responses to customer calls, breakdowns, and emergencies, while proactive work orders are preventive maintenance work. The rate of closed work orders is governed by two balancing feedback loops: “work faster” and “work longer.” When work pressure rises,

productivity and the workweek also rise, decreasing the backlog and lowering work pressure, all else equal.

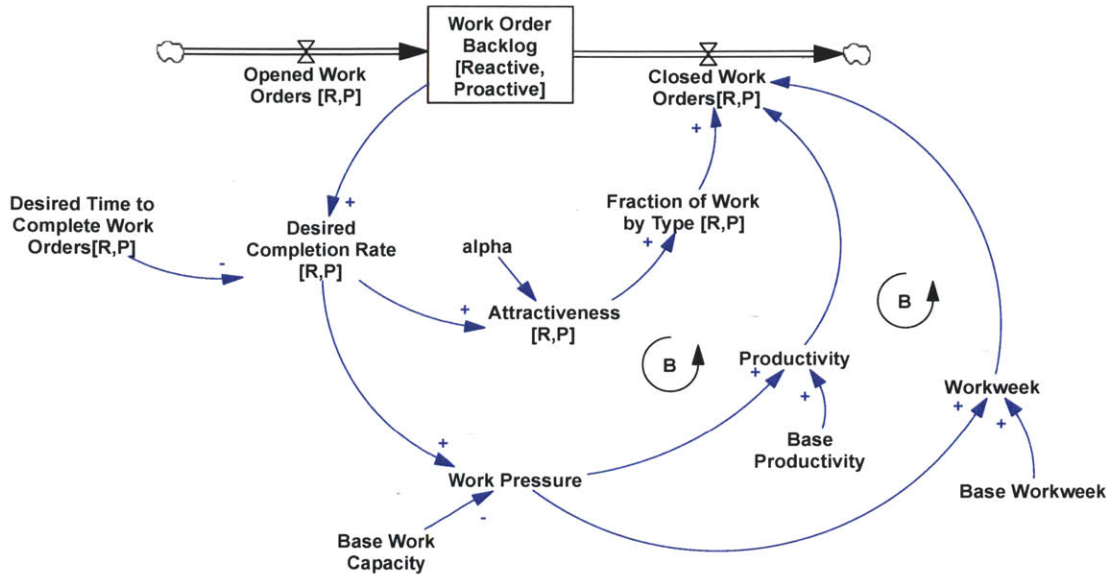


Figure 1: Basic Structure of a Labor Capacitated Process

The *Desired Completion Rate*, Q^* , for each type is the backlog of unfulfilled work orders, B , divided by the desired time to complete work orders, τ :

$$Q_i^* = \frac{B_i}{\tau_i} \tag{1}$$

The parameter τ is a management policy, set to be an average of 2 weeks for reactive work and 4 weeks for proactive work. (A fraction of emergency work orders are completed much more quickly; however, for a simulation with a time horizon of several years it is appropriate to aggregate all reactive work.)

Given a desired completion rate for each type of work, capacity is allocated between reactive and proactive work according to a logit choice model, where the

variable A is the “Attractiveness by Priority” variable shown in Figure 1, f is the fraction of work by type, and Q^* is the desired completion rate defined above:

$$f_i = \frac{A_i}{\sum_j A_j} \quad (2)$$

$$A_i = e^{\alpha Q_i^*} \quad (3)$$

Next, we estimate the relationship between work pressure and productivity from the data. The relationship is given by:

$$p = p_b w^\gamma \quad (4)$$

where p is productivity, p_b is base productivity, w is work pressure, and γ is the sensitivity of productivity to work pressure. Work pressure is the total desired completion rate divided by capacity, and base productivity is the average productivity over the three-year period. We expect $0 \leq \gamma < 1$ because the impact of work pressure on productivity must saturate. We estimate γ using log linear regression; results confirm a statistically significant positive relationship between work pressure and productivity ($\gamma=.14$, $t= 2.71$, $p<.0001$).

A similar procedure is used to formulate the relationship between work pressure and the workweek. The estimate for the sensitivity of the workweek to work pressure, however, is positive but not statistically significant. This result is consistent with both qualitative and quantitative data regarding the use of overtime; overtime is rare, and is more often used for scheduled shutdowns than to catch up on work.

Sources of Work Orders: Equipment Defects

We next expand the model to consider the sources of work orders. In the model, the rate of reactive work orders created, O_R , is the stock of equipment defects D , multiplied by a hazard rate h :

$$O_{R,i} = D_i h_i \quad (5)$$

Conceptually, defects are either known or undiscovered problems that could produce breakdowns and work orders in the future. For example, defects include worn fan belts, broken thermostats, heating systems out of calibration, or loose pipe joints. The model is disaggregated into six categories, corresponding to a standard industry classification scheme. The categories are exterior structures, interior structures, plumbing, electrical, HVAC, and Other.

The initial stock of defects for each category is set so that the initial rate of work orders matches the actual data at the start of the simulation. Conceptually, the hazard rate is the likelihood that a defect will cause a work order in a given time period. The hazard rate varies by category and is higher for electrical, plumbing, and HVAC systems and lower for exterior and interior structures.

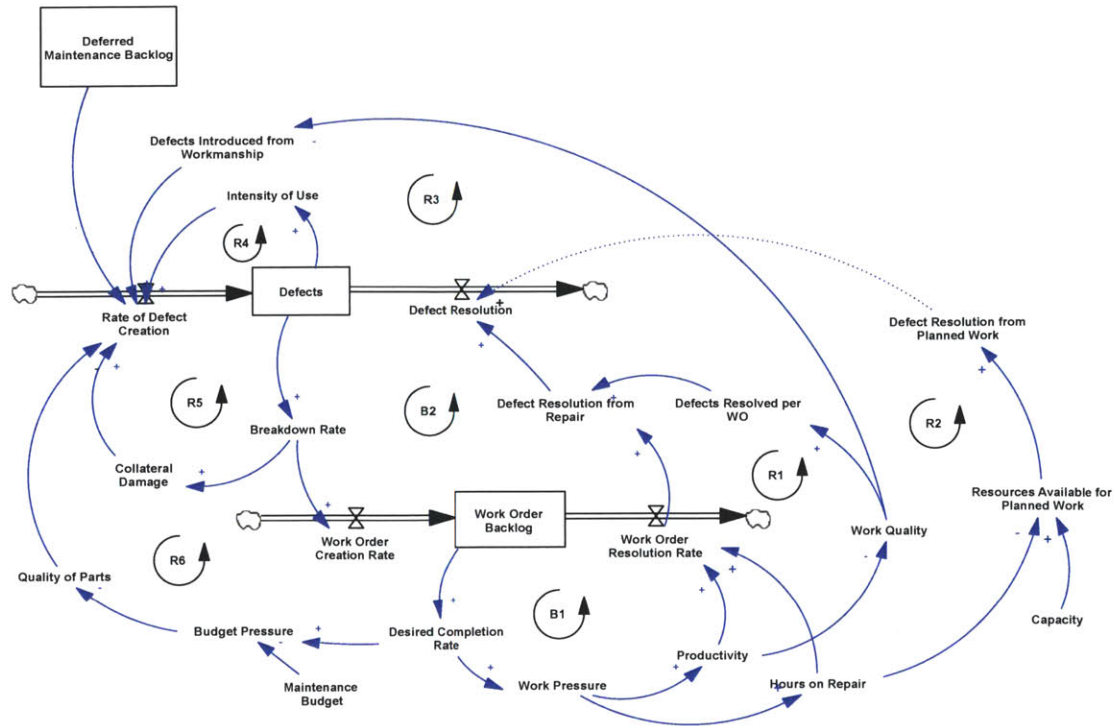


Figure 2: Feedback Relationships Introduced Through Equipment Defects

The addition of the stock of defects introduces several important feedback relationships, as shown in Figure 2. These relationships emerged from interviews and are consistent with practical industry literature (e.g. Levitt 1997) and case studies of maintenance organizations (e.g. Carroll et al. 1997, Ledet 1999). In particular, the reinforcing loop R2 captures the main dynamics of proactive and reactive maintenance. When the variable hours on repair work rises, fewer resources are available for proactive work, leading to fewer defects resolved, a higher stock of defects, more breakdowns, and still more hours on repair. A vicious cycle emerges in which the organization descends into a greater and greater reliance on reactive work and firefighting (Repenning et al. 2001). The same loop, however, can become virtuous: because proactive work is more

productive than reactive work, resources spent on proactive work can reduce defects at a higher rate and thus free up still more resources for proactive work.

Several other reinforcing loops (loops R1 and R3-R6) support this basic dynamic. Loop R1 captures the effect of high work pressure on work quality. When work pressure is high, the maintenance organization may pursue temporary solutions that do not resolve underlying defects. As a result, the stock of defects remains high, leading to more work orders and still higher work pressure. Both quantitative and qualitative data support such a “corner-cutting” effect. As described above, regression analysis of work order data confirms that workers complete work orders on average more quickly when work pressure is high. In addition, interviewees gave numerous examples of such an effect. For example, when customers report that a room that is hot, a mechanic may adjust the temperature without resolving underlying problems in the temperature controls or heating system. Similarly, supervisors report having to continually devote resources to the same temporary fixes on old pumps, rather than make a single, cheaper replacement.

Loops R3-R6 show feedback relationships through the rate of defect *creation*. Breakdowns can cause collateral damage (R5), as in the example of the steam pipe explosion above, and thus introduce new defects. Similarly, when defects are left unresolved, they can cause wear on machinery and infrastructure that introduces new defects (R4). Finally, work and budget pressure can introduce defects through poor quality parts or poor workmanship (R3 & R6). Because the exact strength of these relationships is uncertain, we test the sensitivity of results to variations in the strength of positive feedback. Results are included below.

The Sources of Defects: Infrastructure Renewal

We next consider the sources of defects. As noted above, the university has a large backlog of deferred maintenance, in the form of building systems that remain in place past their recommended useful life and in equipment that has been maintained less frequently than the recommended intervals. To capture the influence of the aging campus on the maintenance organization, we model the aging of building systems directly.

Figure 3 shows the basic stock and flow structure:

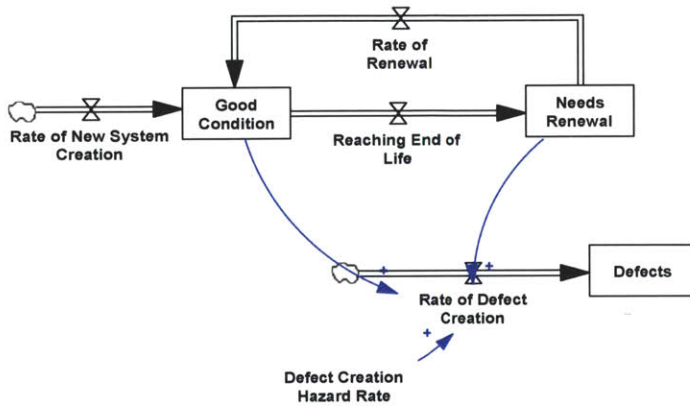


Figure 3: Stock and Flow Structure for Infrastructure Renewal

Each building system is categorized in one of two ways: either the system is in *good condition*, or the system *needs renewal*. When an item reaches the end of its recommended useful life, it ages from the good condition stock to the needs renewal stock. When that item is renewed, it is restored to good condition.

The renewals structure treats each building and building system individually. To populate the model, we use a database commissioned by the university in 2007. The database contains a list of all building systems that will come up for renewal between 2007 and 2030, the year renewal is required, the lifetime of that system, and the cost of renewal. When an item is renewed, the renewal year is adjusted according to the lifetime.

(For example, a system with a lifetime of 10 years that is renewed in 2015 will come up for renewal again in 2025). Finally, because the database lists only building systems that will be due for renewal before 2030, the database excludes some systems in newer buildings that will remain in good condition past 2030. To correct this problem, we introduce items, as described in the appendix.

Defects are created according to the condition of building systems. Specifically, we assume that items that *need renewal* generate defects at a higher rate than items that are in *good condition*. Defects created by each item are aggregated into a flow of defects created for each category. The base rate of defects created, R_b is given by:

$$R_{b,c} = \sum_i^{i \in G,c} i h_G \varepsilon_i + \sum_j^{j \in N,c} j h_N \varepsilon_j \quad (6)$$

where h_G and h_N are hazard rates for the good condition and needs renewal conditions, respectively, i and j are the costs of individual items (we assume that more costly items generate proportionately more defects, within a given category), and ε are random error terms that capture heterogeneity in the quality and wear of individual items. The hazard rates are set so that the initial defect creation rate matches the equilibrium defect removal rate through maintenance. The defect creation rate then grows as items begin to need renewal.

The rate of defect creation, in turn, is influenced by several additional factors described above and shown in Figure 2. We formulate these effects as follows:

$$R_c = R_{b,c} \cdot f(Q_p) \cdot g(U_c) \cdot h(Q_w) + \sum_d (O_d k_{d,c}) \quad (7)$$

In (7), Q_p refers to parts quality, Q_w refers to work quality, U is intensity of use, O_d is the breakdown rate by category, and k is the number of defects produced per breakdown due

to collateral damage. The functions f , g , and h are nonlinear functions (decreasing for Q_p and Q_w and increasing for U) that are linear around an operating point and then saturate. For example, as the intensity of use increases, the rate of defect creation also increases, until a maximum value is reached. Likewise, increasing parts quality decreases the rate of defect creation. Finally, the last term in (7) represents defects created by collateral damage. Each breakdown, O , produces new defects in each category. In other words, a breakdown of HVAC systems might produce breakdowns in interior structures due to a leak that damages ceiling tiles.

Although the level of renewal investment at the university is far too little to address all items that need renewal, the university does invest a sizeable amount in renewal. The renewal investment is a parameter that is assumed to be constant at historical levels. We allocate such investment among items that needs renewal according to a prioritization scheme that allocates funds to the activities with the highest NPV until the renewal budget is exhausted.

Building Energy Use

Finally, we expand the model to capture the energy usage of buildings and the relationship between energy usage and maintenance. Without adequate maintenance, the energy consumption of buildings and equipment rises with age and use: windows crack; insulation compresses; air gaps open in walls and roofs; and ducts and pipes become corroded and leak. Maintenance investments to repair certain defects therefore reduce energy consumption.

We model three major forms of energy consumption: steam, chilled water, and electricity. We first use time series data on campus energy usage between 2000 and 2006 to estimate the rate at which energy consumption rises over time. To do so, we run a panel regression across approximately 100 campus buildings, with time as an independent variable. The regressions include fixed effects for buildings and control for annual heating and cooling degree-days (a measure for the demand for heating and cooling in a given year). Results, presented in Table 1, show a significant positive time trend for all three energy types.

	Chilled Water (Mbtu/GSF)	Electricity (Mbtu/GSF)	Steam (Mbtu/GSF)
Time Trend	0.562** (.1029)	0.461** (.112)	0.005818** (.000802)
Cooling Degree Days	0.00117 (.00163)	0.000309 (.000546)	0.000016** (3.952E-6)
Heating Degree Days	-0.00016 (.0005)	-0.00037 (.00177)	2.961E-6 (.000013)

Table 1: Results of panel regressions of the effect of aging on Building Energy usage. Time trends are significant at the .0001 level. (Building fixed effects are not shown, and are included in the appendix)

Although consumption of all three energy forms rises over time, the relationship between consumption and maintenance differs between the three. In the case of electricity, a substantial portion of increased consumption can be attributed to increased plug loads. Rising steam usage, on the other hand, is almost entirely a consequence of deteriorating building structures and systems. Users have limited discretion to adjust temperature set points, and building activities have not changed in a way that might increase heating demands. Finally, increases in chilled water consumption are likely explained partly by deteriorating building structures and partly by changes in usage.

Although cooling demands are influenced by cracks in windows, air gaps, and leaks in ducts or pipes, the heat caused by rising plug loads may also be a source of some increased usage.

Despite evidence of increasing energy consumption over time, research shows that the effects of wear and aging must also saturate, causing consumption to approach some upper limit. For example, Toole & Claridge (2011) find that savings from a retro-commissioning effort in university buildings decay over a period of ten years in a manner that can be modeled using an exponential form. We capture this process as shown in equation (8):

$$\frac{dE_j}{dt} = \frac{(E_j^* - E_j)}{\tau_j} \tag{8}$$

where E_j is the energy requirement per square foot at a point in time, indexed by type of energy, and E^* is an upper limit to which energy requirements per square foot gradually approach as building maintenance deteriorates. The time constant, τ , reflects the speed with which the upper limit is approached. By our formulation, the lower energy consumption is relative to the limit, the faster consumption rises. Equation (8) is depicted by the equivalent stock and flow diagram shown in Figure 4:

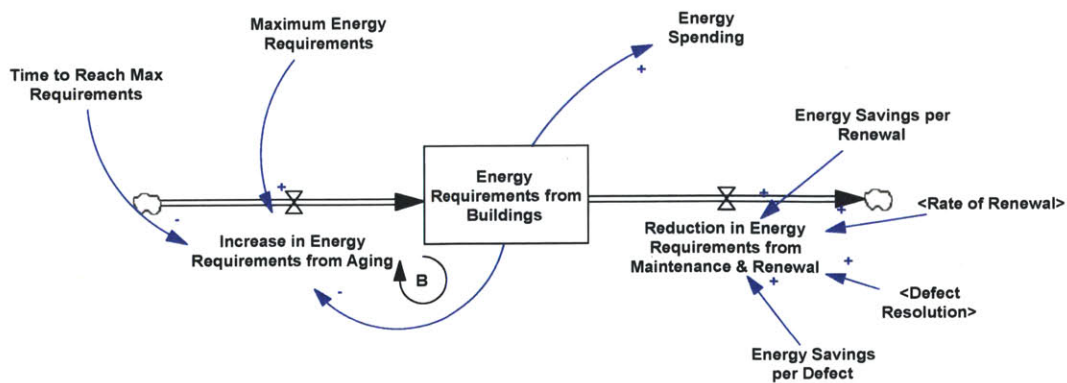


Figure 4: Stock and Flow Structure of Building Energy Requirements

We next estimate the parameters E^* and τ for each of the three forms of energy from the data. To do so, we perform individual regressions for each building to obtain a time trend, and then compare the time trend to the age of the building. If the model in (8) is a good approximation, we expect the time trend to be larger for younger buildings. Table 2 shows the estimates obtained. (Further details are included in the appendix.) Note that the large value of E^* and τ for electricity is consistent with an explanation based on increased plug loads. (The increase in plug loads overwhelms the saturation effect, producing a rise that is effectively linear).

	τ (years)	E^*	E_{2005}	E_0	Potential E Saved	E_{2000}
Chilled Water (Ton-hrs/yr/gsf)	37	20.79	7.48	3.35	4.129 (55%)	5.94
Electricity (Kwh/yr/gsf)	550	253.55	18.58	14.27	4.311 (23%)	17.83
Steam (Klb/yr/gsf)	116	0.675	0.119	0.0695	0.050 (41%)	.095

Table 2: Parameter Estimates and Initial Values for the Energy Model

The final step in formulating the energy model is to link the energy requirements of buildings to maintenance and renewal activities. Just as energy requirements grow over time, energy requirements are also reduced as defects are resolved and renewal activities are undertaken. We look to literature on building commissioning to obtain estimates on the maximum savings that are available (as a percentage of starting energy

usage); such estimates are likely conservative given that commissioning efforts do not target all existing defects. We next allocate potential savings among building systems, based on the judgment of an expert engineer.²

Model Analysis

Simulating a Proactive Investment in Maintenance

We next use the model to simulate a policy of proactive investment in maintenance. We implement the investment by increasing the capacity of the maintenance organization. With increased capacity the maintenance organization can continue to respond as before to breakdowns and emergency repair requests while also devoting more resources to planned work. More planned work reduces the stock of defects. In this test we assume no change in the investment in building renewal – the policy only increases maintenance activity. Although the renewals structure forms a crucial input, the main dynamics are caused by feedback relationships shown in Figure 2.

Figure 5 shows a base run of “business as usual” in which no investment is made. We simulate from 2005 to 2025. The base run captures the current state of the maintenance organization, as described above. Work is highly reactive, and becomes even more so over time as the condition of the campus deteriorates. The stock of defects rises and the organization has to spend more over time to provide the same level of service.

² In an interview setting, we showed engineers a list of building systems from the comprehensive database described above and asked them to rank the relative contribution of each system to energy usage, for each of the three categories. For example, HVAC systems were given a high weight with respect to steam usage.

In addition, Figure 5 compares the base run to a policy of proactive investment. An investment totaling \$9M over a period of 1.5 years is made. (By comparison, maintenance spending – excluding renewals - begins at approximately \$15M per year). The policy assumes that savings are reinvested rather than harvested: after the investment period, spending continues at base levels despite the fact that the volume of reactive work is reduced.

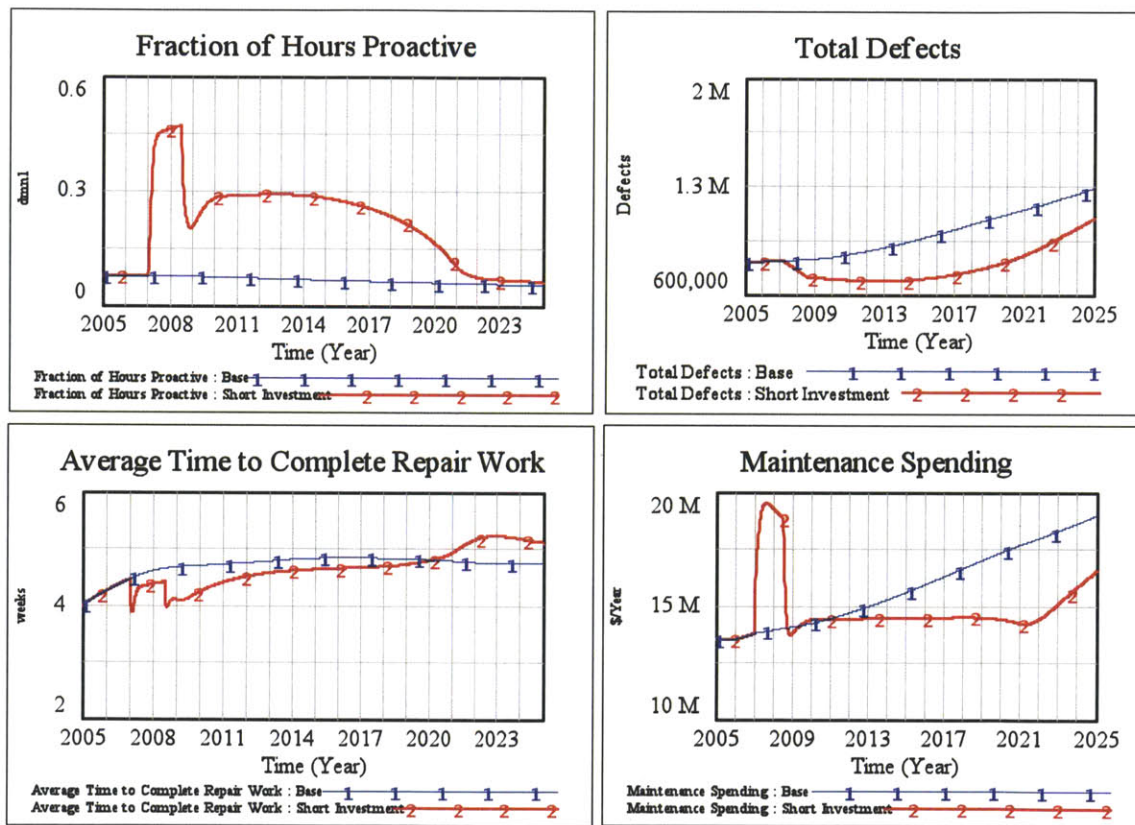


Figure 5: Comparing the base run with a proactive investment of \$9M over a total of two years

The proactive investment causes a temporary improvement both in the state of the campus and in service quality, and decreases energy use about 2%. Yet, over the following ten-year period, the gains from the investment are gradually lost. To

understand why, consider the stock of defects shown in Figure 2. The proactive investment leads to a drop in defects during the two-year period between 2007 and 2009. The drop in defects decreases the breakdown rate, decreases the fraction of time spent on reactive work, increases the fraction of time spent on planned work, and thus increases the overall productivity (defects removed per hour) of the maintenance workforce. The *size* of the increase in productivity, however, is crucial to the subsequent dynamics once the added capacity is removed. Specifically, although the rate of defect elimination is now higher, by 2011 it remains below the rate of defect *creation*, as shown in Figure 6. As a result, the stock of defects begins to rise, causing a return to the vicious cycle described above. The breakdown rate increases, leading to declining productivity and a still higher breakdown rate. Notably, the rising inflow to the stock of defects – a result of underinvestment in renewals – partly precipitates these dynamics.

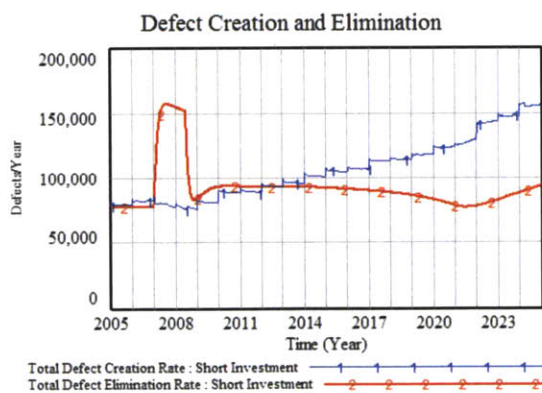


Figure 6: Comparison of the rate of defect creation and defect elimination for the run “Short Investment”

Despite the return of the organization to near previous levels of disrepair, however, the policy is successful financially. We calculate the NPV of the investment by comparing discounted total spending between the base run and the policy run. The policy

brings a NPV of \$25M relative to the base; other investments of a similar size and duration perform similarly. When energy savings are included, the performance is greater still (NPV = \$42M). However, the underlying problem has not been solved; eventually, the university finds itself back in the same trap of high defects and breakdowns, poor quality buildings and equipment, and a high risk of accidents threatening health and safety of employees, students, and others. Moreover, while the return is positive, significant potential gains are left unrealized, as we demonstrate below.

Crossing the Tipping Point: The Impact of Investment Size & Duration

Can a proactive investment produce a sustainable improvement in the state of the campus and in energy efficiency? Building on the analysis above, we experiment with investments that are both larger and longer in duration. Results, shown in Figure 7 and Figure 8, show that both conditions produce superior results. The reduction in the stock of defects (and by extension in energy usage), the reduction in maintenance costs, and the increase in productivity and service quality are more sustainable.

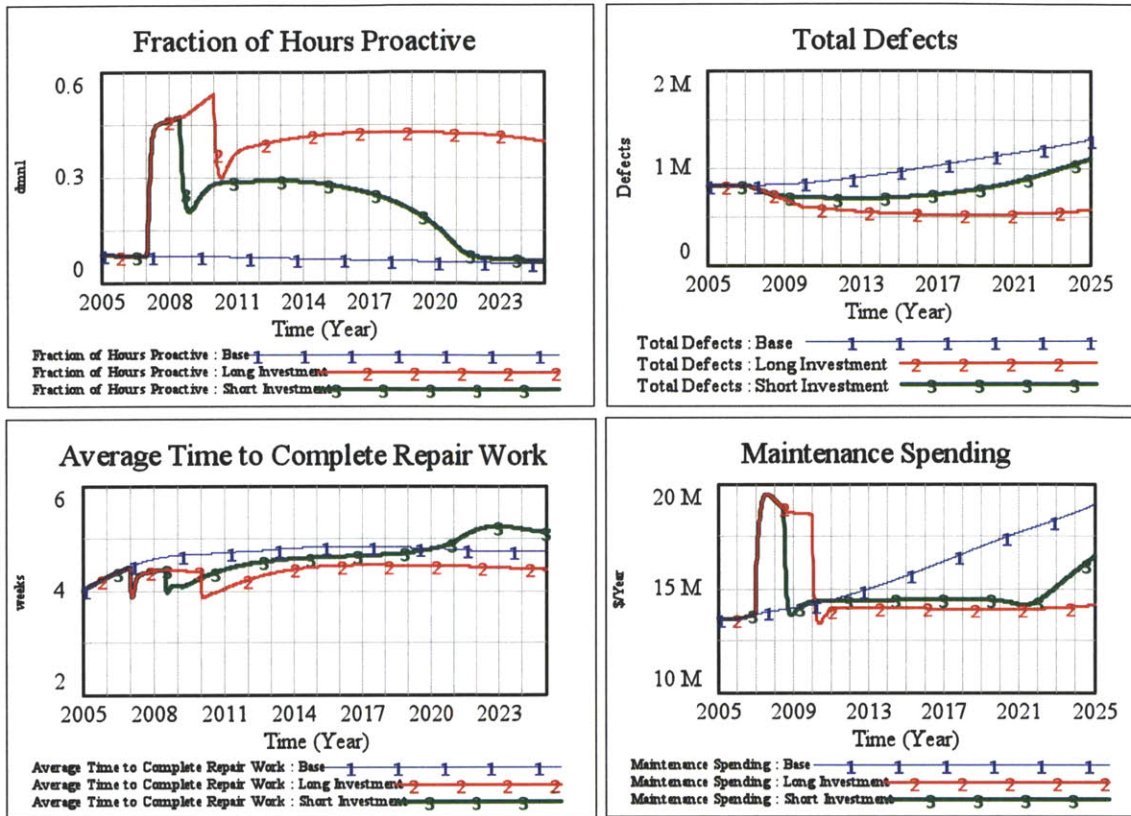


Figure 7: Comparison of a Short and Longer Investment

Figure 8, in particular, shows the existence of a clear tipping point that is crossed as the size of the investment is increased. Building on the logic developed above, when the investment is large enough, the stock of defects is reduced enough during the investment stage such that the system enters the virtuous regime. The outflow of the defects stock exceeds the inflow, allowing work to become increasingly proactive over time. Figure 7 (the longer investment) does show some reversion by the end of the simulation due to the rising inflow; the short and large investment (Figure 8) is more successful at counteracting the effects of the aging campus through feedback loops R3-R6 (work & parts quality, intensity of use, etc.).

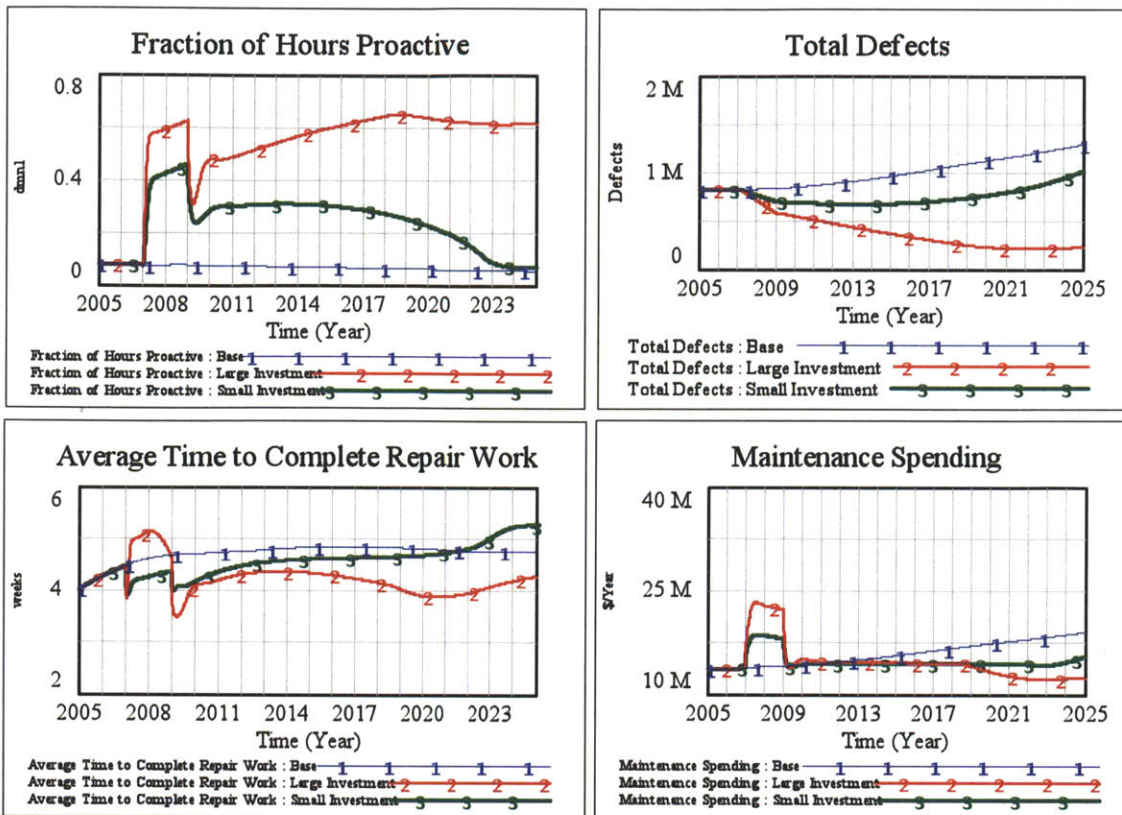


Figure 8: Comparison of a Small and Larger Investment

Despite improved outcomes, however, simulation results for a larger and longer investment provide important insights into why organizations so often fail to achieve sustainable improvement. Consider Figure 7 once again. While a longer investment poses substantial short-term costs, the benefits of the added investment are not readily apparent until many years later. Instead, managers have every temptation to abandon the policy early. For example, consider the vantage point of a manager considering whether to extend the investment midway through 2008. By cutting short the investment, the manager immediately saves on spending. In addition, service quality *improves* (i.e. the average time to complete repair work drops), as resources can now be focused on serving customers. Meanwhile, maintenance spending remains relatively low and the share of

proactive work remains relatively high. Managers might easily *learn* that halting the investment early is a good policy (Repenning & Sterman 2001, 2002). The same is true regarding the size of the investment (Figure 8); in the short run, the smaller investment performs almost as well.

Why doesn't a larger investment allow maintenance spending to be reduced earlier? In both Figure 7 and Figure 8 maintenance spending following the investment remains roughly constant at similar levels for both runs. The answer is that possible savings are instead reinvested in proactive work. In other words, as long as proactive work remains, the organization keeps spending at base levels and invests in further reducing the stock of defects. The budget policy could be adjusted to harvest gains sooner and complete only necessary reactive work; such a policy, however, causes a return much sooner to the vicious cycle of reactive maintenance, and is therefore suboptimal.

The appeal of underinvestment is captured in financial results as well. Figure 9 compares results for several policy runs, including the short, longer, and large investments (we explain reinvestment in energy savings in the next section). Although the longer and larger investments bring substantial value in terms of positive NPV – especially when energy savings are considered – these investments have longer payback times and have a lower return relative to the size of the initial investment (NPV per \$ investment). Because most of the additional value occurs after a number of years, payback time is not reduced.

	Short Investment	Short + Reinvest Energy	Longer Investment	Longer + Reinvest Energy	Large Investment	Large + Reinvest Energy
Size of Initial Investment	9M	9M (+ 48M)	18M	18 M (+ 56M)	20 M	20 M (+ 64 M)
Duration of Initial Investment	1.5 years	1.5 years	3 years	3 years	2 years	2 years
NPV relative to Base	25 M	38 M	41 M	51 M	51.5 M	52 M
Payback Period	11.75 years	(none)	13.5 years	(none)	14.5 years	(none)
NPV per \$ Investment	2.78	NA	2.27	NA	2.58	NA
NPV Including Energy Savings	42 M	104 M	91 M	122 M	125 M	128 M
Payback time Including Energy Savings	8 years	17.5 years	9 years	15.5 years	9 years	13.5 years
Final Fraction of Work Proactive	6%	64%	40%	61%	61%	61%

Figure 9: Summary of Results

Reinvesting Energy Savings

To explore additional opportunities to gain from a proactive investment, we simulate additional policies in which the gains from energy savings are reinvested in maintenance. To implement the policy, energy savings relative to the base run are added continuously to the maintenance budget. In turn, the maintenance budget determines staffing levels and the volume of work completed.

Figure 10 shows simulation results. We compare the short investment from above to an identical investment in which energy savings are reinvested. Results show that reinvestment is sufficient to tip the system into the virtuous regime. The amount of reinvestment can be observed in the graph of maintenance spending over time: spending is higher due to the added resources now invested in proactive work. By the final years

of the simulation, however, the stock of defects is depleted such that spending can be cut back. Once again, benefits are substantial but are highly delayed.

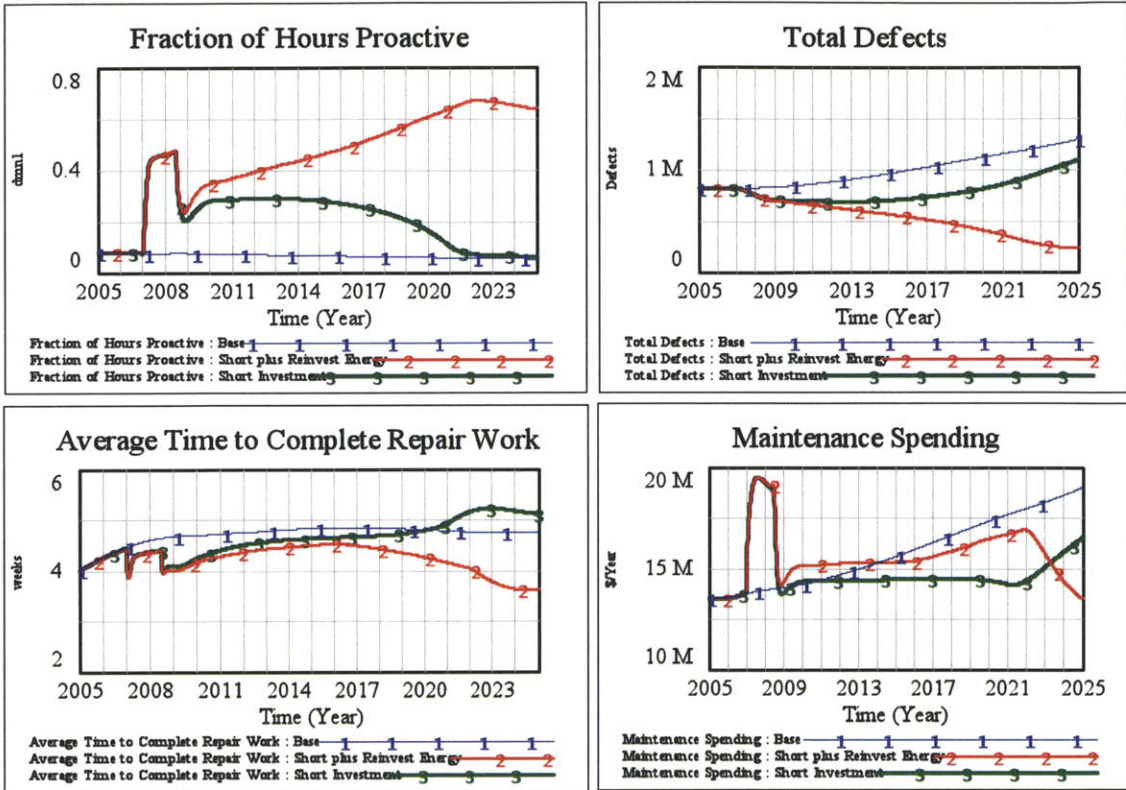


Figure 10: Reinvesting Energy Savings

Figure 9 compares the three policies developed above for the case of reinvesting energy savings. The figures in parentheses next to the initial investment size show the total savings that are reinvested over the course of the simulation. When considering the maintenance sector in isolation, the total investment does not pay back during the course of the simulation. However, the investments do pay back when energy spending is included.

From Figure 9, it is apparent that reinvesting energy savings can be a highly effective strategy. In particular, reinvestment allows the organization to make a much smaller initial investment and still achieve superior outcomes. While the gains from reinvestment in the case of the large and longer investment are relatively modest (the behavior of the system has already tipped into the virtuous regime), reinvestment brings a large improvement for the short investment. Reinvestment itself forms a positive feedback loop that in turn supports other loops: as defects are resolved, energy savings increase, leading to still more investment in reducing defects and still more energy savings. The prevalence of positive feedback in the reinvestment runs helps to counteract the growing inflow of defects due to the aging campus.

Although the reinvestment policies are highly NPV positive, as above reinvestment poses substantial implementation challenges for managers. Because savings are reinvested, they cannot be used to pay back the investment early. In addition, during the early years the system again performs almost as well in the absence of reinvestment, creating an incentive to abandon the policy early.

Sensitivity Analysis: The Strength of Positive Feedback

Finally, we examine the sensitivity of model results to several key parameters. Model analysis reveals several parameters that influence the magnitude and qualitative character of outcomes. The particular value of these parameters will influence the attractiveness of opportunities for investment in different contexts.

First we consider parameters for productivity and cost of reactive and proactive work. We use data on the average costs and labor hours required across categories of

work to set these parameters; however, in different contexts the gap could be smaller or larger. The magnitude of the gap has an important influence on model results. The more productive proactive work is relative to reactive work, the stronger the basic positive feedback process (R2 in figure 2) that drives improvement (or decline). For example, an investment that reduces the rate of breakdowns will free resources for more or less proactive work, generating a smaller or larger decline in the rate of future breakdowns. The larger the gap, the sooner model behavior will tip into the virtuous regime and the more favorable financial results across all runs will be.

The strength of the additional reinforcing feedback loops shown in Figure 2 also has an important influence on model results. In particular, reinforcing loops through the rate of defect creation are essential to counteract the influence of the aging campus. As noted above, these relationships are more uncertain and require future study. How do part quality and work quality influence future defects (R3 & R6)? How quickly do part and work quality respond to work and budget pressures? If defects are left unresolved, to what extent are larger defects created through increased wear (R4)?

Figure 11 shows the sensitivity of model results to a change in the strength of positive feedbacks R3, R4, and R6. To vary the strength, we adjust the slope of the functions f , g , and h in equation (7) above. For example, a steeper slope in f means that an increase in parts quality causes a proportionately greater decrease in the rate of defects created. Results show that weaker positive feedback can speed the return of reactive work, or possibly prevent behavior from tipping into the virtuous regime. Although the two runs in Figure 11 produce similar financial results when maintenance is considered

alone (less so when energy savings are included), improvement in service quality and in energy usage is more sustainable in the case of stronger feedback.

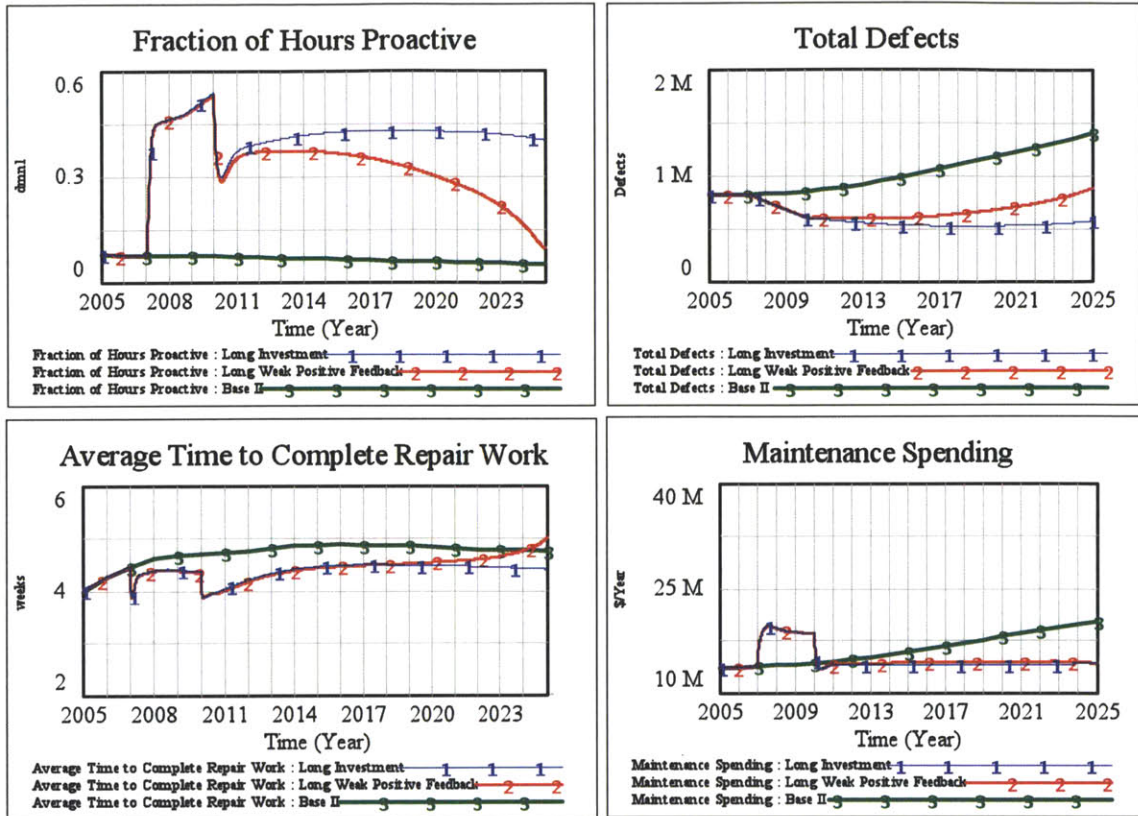


Figure 11: Weakening the strength of Positive Feedback

Beyond parameters related to the strength of the positive feedback, results are also sensitive to several parameters regarding building renewal and energy use. First, the two hazard rates shown in equation 6 govern the influence of aging on defect creation. We assume that building systems in the NR category create more defects per unit time than systems in good condition; the size of this gap governs how fast the inflow to the stock of defects rises, and thus how likely the model is to tip into the virtuous regime.

Second, the magnitude of energy savings is sensitive to assumptions regarding the link between energy usage and maintenance. As noted, we show that energy usage increases with aging, and then assume that a fraction of gains can be reversed through maintenance. This fraction is an important parameter that could be adjusted based on

more detailed engineering analyses. Although significant savings have been achieved and documented in individual building systems, detailed engineering studies of the entire campus do not yet exist. Despite uncertainties in the exact magnitude of energy savings, however, it is important to note that proactive investments in maintenance are NPV positive even when energy savings are not included. In addition, the recent success of several building commissioning efforts suggests that potential energy savings from maintenance are in fact substantial.

Discussion & Conclusion

Why do organizations so often fail to capitalize on potential “win-win” investments? The case of building maintenance yields new insights into the management challenges that proactive investments can produce. To start, the case of building maintenance is not well explained by existing theories of organizational inaction or by the standard economic accounts of these failures. First, managers are well aware of the benefits that increased proactive maintenance can produce, in terms of reduced maintenance costs, improved service quality and reduced energy usage. Second, the financial benefits are real and substantial, even when future earnings are appropriately discounted. Finally, pressures or biases that favor short-termism tell only part of the story. Although the payback times shown above are relatively long, universities should be uniquely positioned to make investments with a long-term payoff. Endowments are often invested over long time horizons, and universities can expect to occupy buildings many years into the future. More broadly, organizations often do make large capital investments with long payback times when investments serve core organizational goals.

We argue that an analysis of the dynamics of improvement provides crucial insight into the pressures that can impede proactive investments. Specifically, simulation results show that managers might easily choose to abandon proactive investments early, before the organization can cross the tipping threshold and escape the capability trap. While abandoning an investment early provides an immediate return, lost opportunities to achieve even greater returns become apparent only gradually. Given the typical time path of returns, it can be extremely difficult for managers to determine when important tipping thresholds are crossed. Managers in uncertain environments may begin to cut investment, see performance stabilize, and easily conclude that the investment was a success - even as performance once again begins to decay.

The dynamics described above apply to a wide variety of proactive investments, including many that contribute to regulated outcomes and social goals. Although some investments in safety or environmental performance are simple technological upgrades, many others entail substantial organizational change efforts. For example, new technologies may cause disruptive and unpredictable changes to work routines and intergroup relationships (e.g. Barley 1986, Orlikowski 1992). New organizational structures that support compliance with regulation – such as compliance offices and safety and environmental management systems – can produce similar effects (Kelly & Dobbin 2007, Huising & Silbey 2011). To make these technologies and management systems effective, organizations often must devote sizable resources towards learning to operate new technologies and resolving disagreements and interpretation challenges that emerge. Underinvestment in these areas can cause resistance and conflict that can limit effectiveness (Essay 1 of this dissertation). In general, improvement efforts in

organizations often display tipping point dynamics much like those described in the case of building maintenance (e.g. Repenning 2002, Repenning & Sterman 2002).

A fuller understanding of the dynamics of proactive investment raises important implications for theories of self-regulation and corporate social responsibility, and has major practical implications for policies to reduce energy use, GHG emissions and other forms of pollution. Scholars have long recognized that some organizations outperform others with regard to regulated and socially beneficial outcomes, even within the same industry and regulatory environment (e.g. Gunningham et al. 2003). Understanding such variation, however, has proven to be a more difficult challenge. Management scholars point to differences in technical competency (Christmann 2000) or differences in local institutional pressures or legal environments (Bansal 2005, Marquis et al. 2007, Short & Toffel 2010) as important factors. Yet, structural explanations can only go so far. In addition, the literature on self-regulation also attributes variation to differences in the *commitment* of managers and internal activists who must locate, advocate for, and implement improvements (Roome 1992, Henrique & Sadorsky 1999, Parker 2002, Gunningham et al. 2003).

Explanations based on management commitment, however, leave important questions unaddressed. While it is easy to understand the sources of proactive behavior, the motivations of those who are *not* proactive are at times puzzling. Specifically, why would any manager leave profitable, well-known investment opportunities on the table?

Our findings add insight into the specific features of management agency with regard to self-regulation and social responsibility. Beyond an awareness of improvement opportunities, adequate capital and sufficient insulation from short-term pressures, we

suggest that managers must also possess an understanding of the complex dynamics that can govern improvement efforts. Research shows that very often such understanding is lacking (Repenning & Sterman 2001). Actors in complex systems routinely misperceive the effects of accumulations, time delays and feedback relationships on behavior, with adverse effects for decision-making and outcomes (Sterman 1989, Paich & Sterman 1993, Moxnes 1998, Cronin et al. 2009). Given the complexity of most self-regulation efforts, such misperceptions can help to distinguish between organizations that are able to demonstrate commitment, and those that are not.

These results provide useful practical implications both for managers and for regulators. First, wherever possible, managers must recognize the long delays that exist between investment and full improvement, and resist the urge to under-invest or cut investments short. Simulation models such as the one developed here can provide valuable insight into the existence of tipping dynamics and aid decision makers in finding paths towards sustainable and profitable outcomes. Second, wherever possible, managers should seek to reinvest gains in future improvement rather than harvest savings early. In the case developed above, reinvesting energy savings back into buildings generates powerful positive feedbacks that contribute to improved outcomes. By reinvesting savings, managers can achieve positive outcomes with less of an upfront investment. Although not harvesting savings can lengthen investment payback times, reinvestment can increase the total value that is ultimately recovered. Finally, regulators might build on these insights to develop more effective regulatory strategies. For example, regulators might search for methods to measure and encourage long-term investment without demanding or rewarding results too quickly. Quick and early successes should be treated

with skepticism if they are not likely to be sustainable. In addition, regulators might design policies that encourage reinvestment of savings.

The analysis presented above has several limitations. First, while many proactive investments are profitable in the manner described, it is important to recognize that some others may not be, at least in a narrow financial sense. For example, many essential efforts to improve safety and environmental performance will entail costs that are not recovered over time in the form of reduced operating or energy expenses. Still, such investments may bring other non-financial or less easily quantified benefits that do make them worthwhile.

Second, the example here, while broadly illustrative of many other settings, remains a single case study. The simulation model developed above is a highly specific model of a building maintenance system. Future studies might explore how the general dynamics that we describe apply in more detail to other types of proactive change.

Finally, it is important to note that the dynamics described above to some extent describe potential future behavior rather than behavior that has already occurred. Our model is calibrated to a wide range of existing data, but the policies described have only partially been enacted. MIT has begun to increase funding for proactive maintenance, tackle its deferred maintenance backlog, and identify opportunities to reduce energy consumption. Yet, these efforts are only beginning, and only time will tell whether the size of investments or the degree of reinvestment will be sufficient to allow the organization to cross the tipping threshold. Future research might compare actual cases after the fact of investments that are either successful or are cut short.

Proactive “win-win” investments represent one of the most promising avenues by which organizations can become more socially responsible actors. Identifying these opportunities and understanding barriers to implementation thus presents an excellent opportunity for both practical action and scholarly research.

References

- Amin, S. M. 2011. "US grid gets less reliable." *IEEE Spectrum* 48(1):80.
- Bansal, P. 2005. "Evolving sustainably: a longitudinal study of corporate sustainable development." *Strategic Management Journal* 26(3):197–218.
- Barley, S.R. 1986. "Technology as an occasion for structuring: Evidence from observations of CT scanners and the social order of radiology departments." *Administrative science quarterly* 31(1):78–108.
- Carroll, J. S, J. Stermann, and A. Marcus. 1997. "Playing the maintenance game: How mental models drive organizational decisions." in *Debating Rationality: Nonrational Aspects of Organizational Decision Making*, edited by R Stern and J Halpern. Ithaca: Cornell University Press.
- Charles, Dan. 2009. "Leaping the efficiency gap." *Science* 325(5942):804–811.
- Christmann, Petra. 2000. "Effects of 'Best Practices' of Environmental Management on Cost Advantage: The Role of Complementary Assets." *The Academy of Management Journal* 43(4):663–680.
- Coglianesi, C., and J. Nash. 2001. *Regulating from the inside: can environmental management systems achieve policy goals?* Washington, DC: Resources for the Future.
- Creys, J. C., A. Derkach, S. Nyquist, K. Ostrowski, and J Stephenson. 2007. *Reducing US Greenhouse Gas Emissions: How Much at What Cost?* McKinsey & Company Retrieved (http://www.mckinsey.com/client_service/sustainability/latest_thinking/reducing_us_greenhouse_gas_emissions).
- Cronin, M. A., C. Gonzalez, and J. D. Stermann. 2009. "Why don't well-educated adults understand accumulation? A challenge to researchers, educators, and citizens." *Organizational Behavior and Human Decision Processes* 108(1):116–130.
- Cyert, R. M, and J. G March. 1963. *A behavioral theory of the firm*. Englewood Cliffs, NJ: Prentice Hall.
- Effinger, J., H. Friedman, and D. Moser. 2009. *A study on energy savings and measure cost effectiveness of existing building commissioning*. Portland Energy Conservation, Inc. Retrieved June 14, 2012 (http://www.peci.org/sites/default/files/annex_report.pdf).
- Estlund, C. 2010. *Regoverning the Workplace: from Self-regulation to Co-regulation*. New Haven, CT: Yale University Press.

- Freeman, J., E. R. Larsen, and A. Lomi. 2012. "Why is there no cannery in 'Cannery Row'?" Exploring a behavioral simulation model of population extinction." *Industrial and Corporate Change* 21(1):99–125. Retrieved August 23, 2012.
- Gillingham, K., R. G. Newell, and K. Palmer. 2009. *Energy Efficiency Economics and Policy*. Washington, DC: Resources for the Future Retrieved August 23, 2012 (<http://www.nber.org/papers/w15031>).
- Gunningham, N., R. A. Kagan, and D. Thornton. 2003. *Shades of green: business, regulation, and environment*. Palo Alto, CA: Stanford University Press.
- Hart, S. L. 1995. "A Natural-Resource-Based View of the Firm." *Academy of Management Review* 20(4):986–1014.
- Hawken, P., A. B. Lovins, and L. H. Lovins. 1999. *Natural Capitalism: Creating the Next Industrial Revolution*. Boston: Little, Brown and Co.
- Henriques, Irene, and Perry Sadorsky. 1999. "The Relationship between Environmental Commitment and Managerial Perceptions of Stakeholder Importance." *The Academy of Management Journal* 42(1):87–99. Retrieved June 14, 2012.
- Heo, Y., R. Choudhary, and G.A. Augenbroe. 2012. "Calibration of building energy models for retrofit analysis under uncertainty." *Energy and Buildings* 47(0):550–560. Retrieved May 26, 2012.
- Howard-Grenville, J. A. 2007. "Developing issue-selling effectiveness over time: Issue selling as resourcing." *Organization Science* 18(4):560–577.
- Howarth, R. B., and A. H. Sanstad. 1995. "Discount rates and energy efficiency." *Contemporary Economic Policy* 13(3):101–109. Retrieved August 23, 2012.
- Huising, R., and S. S. Silbey. 2011. "Governing the gap: Forging safe science through relational regulation." *Regulation & Governance* 5(1):14–42.
- Jaffe, A. B., and R. N. Stavins. 1994. "The energy-efficiency gap What does it mean?" *Energy Policy* 22(10):804–810. Retrieved August 23, 2012.
- Jaffe, A., R. G. Newell, and R. N. Stavins. 2004. "The Economics of energy efficiency." Pp. 79–90 in *Encyclopedia of Energy*, edited by C Cleveland. Amsterdam: Elsevier Retrieved August 23, 2012 (http://resume.marcbrands.com/classfolder/45-859/https@blackboard.andrew.cmu.edu/courses/1/s04-45859/content/_185112_1/economics_of_energy_efficiency.pdf).
- Kelly, E.L., and F. Dobbin. 2007. "How to stop harassment: Professional construction of legal compliance in organizations." *American Journal of Sociology* 112(4):1203–1243.

- Kinsley, M. 2009. *Accelerating Campus Climate Initiatives*. Rocky Mountain Institute.
- Ledet, W. J. 1999. "Engaging the Entire Organization Key to Improving Reliability." *Oil & gas journal* 97(21):54–57.
- Levitt, J. 2009. *Handbook of Maintenance Management*. New York, NY: Industrial Press.
- Marquis, Christopher, Mary Ann Glynn, and Gerald F. Davis. 2007. "Community Isomorphism and Corporate Social Action." *Academy of Management Review* 32(3):925–945.
- Martani, Claudio, David Lee, Prudence Robinson, Rex Britter, and Carlo Ratti. 2012. "ENERNET: Studying the dynamic relationship between building occupancy and energy consumption." *Energy and Buildings* 47(0):584–591. Retrieved May 26, 2012.
- Mills, E. 2011. "Building Commissioning: A Golden Opportunity for Reducing Energy Costs and Greenhouse-gas Emissions." *Energy Efficiency* 4(2):145–173.
- Morecroft, J. 2007. *Strategic modelling and business dynamics: a feedback systems approach*. West Sussex, England: John Wiley & Sons Retrieved August 23, 2012 (<http://books.google.com/books?hl=en&lr=&id=-1OiTH90U48C&oi=fnd&pg=PR18&dq=morecroft+modelling&ots=HyuRpeh6Go&sig=QXcklZQtg6hTPtLCXbU7tjigTZA>).
- Moubray, J. 1997. *Reliability-centered maintenance*. New York, NY: Industrial Press Inc. Retrieved August 23, 2012 (<http://books.google.com/books?hl=en&lr=&id=bNCVF0B7vpIC&oi=fnd&pg=PR11&dq=moubray+maintenance&ots=28SnCKbc5B&sig=PqSr38goTmQM3jyarN4oTBPA8Gg>).
- Moxnes, E. 1998. "Not Only the Tragedy of the Commons: Misperceptions of Bioeconomics." *Management Science* 44(9):1234–1248.
- Oliva, R., and J. D. Sterman. 2001. "Cutting corners and working overtime: Quality erosion in the service industry." *Management Science* 47(7):894–914.
- Orlikowski, W. J. 1992. "The duality of technology: Rethinking the concept of technology in organizations." *Organization science* 3(3):398–427.
- Paich, M., and J. D. Sterman. 1993. "Boom, bust, and failures to learn in experimental markets." *Management Science* 39(12):1439–1458.
- Parker, C. 2002. *The Open Corporation: Effective Self-Regulation and Democracy*. Cambridge: Cambridge University Press.

- Pérez-Lombard, Luis, José Ortiz, and Christine Pout. 2008. "A review on buildings energy consumption information." *Energy and Buildings* 40(3):394–398. Retrieved May 26, 2012.
- Porter, M. E., and C. Van der Linde. 1995. "Toward a new conception of the environment-competitiveness relationship." *The Journal of Economic Perspectives* 9(4):97–118.
- Repenning, N. P. 2002. "A Simulation-Based Approach to Understanding the Dynamics of Innovation Implementation." *Organization Science* 13(2):109–127.
- Repenning, N. P., and J. D. Sterman. 2002. "Capability traps and self-confirming attribution errors in the dynamics of process improvement." *Administrative Science Quarterly* 47(2):265–295.
- Repenning, N. P., P. Goncalves, and L. J. Black. 2001. "Past the Tipping Point: The Persistence of Firefighting in Product Development." *California Management Review* 43(4):44–67.
- Repenning, N. P., and R. M. Henderson. 2010. "Making the Numbers? 'Short Termism' & the Puzzle of Only Occasional Disaster." *Harvard Business School Working Paper* (No. 11-033).
- Repenning, N. P., and J. D. Sterman. 2001. "Nobody Ever Gets Credit for Fixing Problems that Never Happened." *California Management Review* 43(4):64.
- Roome, N. 1992. "Developing environmental management strategies." *Business Strategy and the Environment* 1(1):11–24.
- Rudolph, J. W., J. B. Morrison, and J. S. Carroll. 2009. "The dynamics of action-oriented problem solving: linking interpretation and choice." *The Academy of Management Review* 34(4):733–756.
- Sastry, M. A. 1997. "Problems and paradoxes in a model of punctuated organizational change." *Administrative Science Quarterly* 42(2):237–275.
- Short, J. L., and M. W. Toffel. 2010. "Making self-regulation more than merely symbolic: The critical role of the legal environment." *Administrative Science Quarterly* 55(3):361–369.
- Sterman, J. D. 2000. *Business dynamics: Systems thinking and modeling for a complex world with CD-ROM*. Chicago, IL: Irwin/McGraw-Hill.
- Sterman, J. D. 1989. "Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment." *Management science* 35(3):321–339.

- Sterman, J. D., N. P. Repenning, and F. Kofman. 1997. "Unanticipated side effects of successful quality programs: Exploring a paradox of organizational improvement." *Management Science* 43(4):503–521. Retrieved August 23, 2012.
- Sutherland, R. J. 1991. "Market barriers to energy-efficiency investments." *The Energy Journal* 12(3):15–34. Retrieved August 23, 2012.
- TIAX LLC. *Energy impact of commercial building controls and performance diagnostics: Market characterization, energy impact of building faults and energy savings potential*. TIAX LLC Retrieved May 26, 2012 (http://s3.amazonaws.com/zanran_storage/www.tiaxllc.com/ContentPages/42428345.pdf).
- Toole, Cory, and David Claridge. 2011. "The Persistence of Retro-commissioning Savings in Ten University Buildings." Retrieved June 14, 2012 (<http://repository.tamu.edu/bitstream/handle/1969.1/128798/ESL-IC-11-10-69.pdf?sequence=1>).
- Yates, S. M., and E. Aronson. 1983. "A social psychological perspective on energy conservation in residential buildings." *American Psychologist* 38(4):435. Retrieved August 23, 2012.

Appendix – Technical Documentation for Essay 3

The following document provides additional technical details for the model developed in the paper *Giving up Too Soon: The Failure of Win-Win Investments in Process Improvement and Industry Self-Regulation*.

First, we outline additional assumptions for several model sectors. Second, we provide a full presentation of model sector diagrams and model equations.

Maintenance Work Orders and Defects Structure

Collateral Damage Matrix

The formulation for the rate of defect creation (Equation (7) in the text) includes a term for defects introduced through collateral damage. We choose parameters such that 1) the relative values in the matrix below match those provided in expert interviews and 2) the overall rate of defect creation is such that the model begins in equilibrium. The following parameters are used for collateral damage:

		Breakdown Category				
		Exterior, Substructure	Interior Structures & Finishes	Plumbing	HVAC	Electrical
Defects Created Category	Exterior, Substructure	0	0	0.05	0.05	0
	Interior Structures & Finishes	0	0	0	0	0
	Plumbing	0	0.05	0.05	0	0
	HVAC	0	0	0.05	0.05	0
	Electrical	0	0	0	0.05	0.05

Table 1: The Collateral Damage Matrix

Hazard Rates and Time Constants for Building System Categories

We assume that defects in different categories produce workorders at different rates. A defect is defined as a problem that can be reduced through one workorder. (Thus, large and expensive problems would count as multiple defects). The parameters chosen are as follows:

Category	Workorders created /year/Defect
Exterior, Substructure	.06
Interior Structures & Finishes	.07
Plumbing	.134
HVAC	.125
Electrical	.06

Table 2: Hazard Rates for Building System Categories

The smaller figures for exterior and interior structures and for electrical reflect a longer average residence time in the defects stock. That is, an “exterior” defect on average will reside multiple years before producing a breakdown. The long residence time of most defects provides an opportunity for preventive maintenance: defects can very often be spotted and corrected proactively before they cause breakdowns. (We do assume a minimum average residence time of 2 years: that is, the maximum rate of defect elimination through preventive maintenance is the stock divided by two years. This assumption reflects the fact that defects cannot always be spotted immediately.)

Allocating Proactive Work Among Building System Categories

The model endogenously allocates available work hours among categories. The formulation works as follows. First, we calculate available capacity by comparing work capacity to the current desired completion rate for reactive work. Then, based on available work hours, proactive work orders are created. We allocate proactive work hours among categories based on the ‘attractiveness’ of each category.

$$Share_i = A_i / \sum_j A_j$$

$$A_i = c_i * BR_i * p_i \quad (1,2)$$

In equation (2), BR is the breakdown rate for each category (workorders/year), p is the productivity (workorders/hour), and c is a constant reflecting the relative importance of the category to building customers. In other words, proactive work is allocated first to categories that are producing the largest number of work hours, weighted by category importance. ‘Importance’ is highest for HVAC, plumbing, and electrical, and is lower for exterior and interior structures. We assume that customers are more sensitive to breakdowns in these categories (e.g. leaks, hot and cold calls).

Infrastructure Renewal Structure

Resolving Right-Censoring in Individual Building System Data

As noted in the main text, the database of building systems is right-censored. That is, the database includes only those systems that will need renewal before 2030. The database thus omits systems with long life spans in newer buildings, and systems in older buildings that have recently been renewed.

Because we run simulations only through 2025, all systems that would enter the “needs-renewal” stock during the course of the simulation are fully accounted for. However, the “good-condition” stock is understated. Because both items in good condition and items needing renewal produce defects, we must add items to the good condition stock in order to fully represent the rate of defect creation.

To add items, we compare newer and older buildings within the database. We expect that older buildings will have more items with long life spans that will come up for renewal prior to 2030. For example, items with a life span of 75 years would come up for renewal in a building built in 1950, but not in a building built in 1980. Although some items in older buildings may have been renewed already and thus might also be omitted, we assume that the database is complete for old buildings. (A fair assumption given the relative lack of investment in renewal.)

Figure 1 compares old and new buildings, and confirms the absence of longer life-span items in newer buildings:

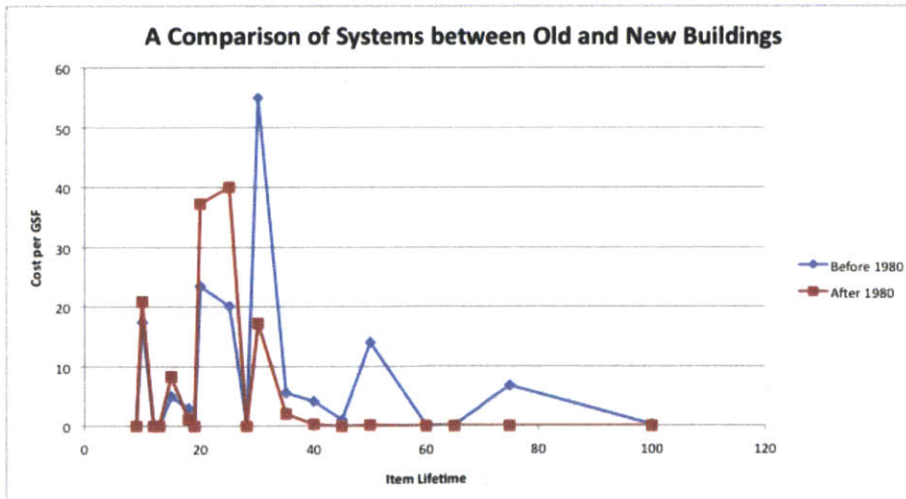


Figure 1: Comparison of Systems between Old and New Buildings

Based on this chart, we introduce longer life span items for all buildings built after 1980. We use the gross square foot of each building to calculate a total dollar value and number of items to introduce, and then assign an appropriate life span. Items in a given category are assumed to have the same average cost per gross square foot across all buildings.

Allocating Renewal Dollars Among Items

The university does invest annually in some renewal projects. The amount invested in renewals is a parameter that can be adjusted. Although the main proactive investments developed in the paper are investments in maintenance, the renewals structure is an important driver of defects. We assume constant spending on renewals throughout the simulation; however, spending could be adjusted to test investment scenarios.

To allocate renewal investment dollars among items, we once again construct an attractiveness measure for each item. The priority of each item is the NPV of potential savings from renewal as a fraction of the renewal cost:

$$Priority_i = (NPV \text{ of Savings}_i - \text{Renewal Cost}_i) / \text{Renewal Cost}_i \quad (3)$$

The model also contains an option to prioritize items randomly for the sake of comparison. For all runs shown in the paper, we use equation (3). In addition, the NPV of savings can include savings from work orders avoided, energy savings, or both. In the base run, we consider only savings from work orders avoided.

To calculate the NPV of work orders avoided, we use the following:

$$\begin{aligned} \text{Rate of Costs Saved}_i &= (\text{DCR}_{\text{NR},i} - \text{DCR}_{\text{GC},i}) * h_c * \text{Cost per WO}_c * \tau_c \\ \text{NPV of Savings}_i &= \frac{\text{Rate of Costs Saved}_i}{r} (1 - e^{(-r * \text{Renewal Life}_i)}) \end{aligned} \quad (4,5)$$

The rate of costs saved is the difference in the defect creation rate (DCR) between needs renewal and good condition, multiplied by the hazard rate (h), the cost per work order, and the average residency of a defect in the stock of defects. The exponential term in the formula for the NPV of savings reflects the fact that savings will persist only as long as the item remains in good condition: in other words, an item with a lifetime of ten years will create savings for ten years before it reenters the needs renewal stock.

After a priority is calculated for all items, the items are ranked. Renewal dollars are then allocated to items according to rank: the highest ranked item is funded first; the second highest ranked item is funded second; and so on. We use the “Allocate by Priority” algorithm in the Vensim modeling software to implement this formulation. More details are available in the Vensim software documentation.

Building Energy Consumption Structure

Results of Panel Regressions on the Effect of Aging on Energy Use

The main evidence for the effect of building aging on energy use is a panel regression that we run across approximately 100 campus buildings, over seven years of data, for three types of energy usage: Chilled Water, Electricity, and Steam. We include fixed effects for individual buildings and for heating and cooling degree-days. Below are the full regression results, including building fixed effects:

a) Dependent Variable: Chilled Water per GSF

Variable	Estimate	Standard Error	t Value	Pr > t
CS1	2.665655	2.4924	1.07	0.2856
CS2	2.249141	2.4924	0.90	0.3675
CS3	9.130657	2.4924	3.66	0.0003
CS4	2.377287	2.4924	0.95	0.3409
CS5	11.4353	2.4924	4.59	<.0001
CS6	0.186468	2.4924	0.07	0.9404
CS7	10.54404	2.4924	4.23	<.0001
CS8	10.29799	2.4924	4.13	<.0001
CS9	5.861007	2.4924	2.35	0.0193
CS10	1.773518	2.4924	0.71	0.4772
CS11	2.078649	2.4924	0.83	0.4049
CS12	4.163414	2.4924	1.67	0.0958
CS13	10.7412	2.4924	4.31	<.0001
CS14	1.162258	3.0328	0.38	0.7018
CS15	4.50627	2.4924	1.81	0.0715
CS16	3.49626	2.4924	1.40	0.1616
CS17	1.207745	2.4924	0.48	0.6283
CS18	6.788243	2.4924	2.72	0.0068
CS19	4.576603	2.4924	1.84	0.0672
CS20	6.895887	2.4924	2.77	0.0060
CS21	30.5775	2.4924	12.27	<.0001
CS22	2.146807	2.4924	0.86	0.3897
CS23	3.223238	2.4924	1.29	0.1968
CS24	-1.23113	3.0328	-0.41	0.6850
CS25	5.138785	2.4924	2.06	0.0400
CS26	2.053204	2.4924	0.82	0.4106
CS27	3.661614	2.4924	1.47	0.1427
CS28	12.30846	2.4924	4.94	<.0001
CS29	6.752057	2.4924	2.71	0.0071
CS30	5.865578	2.4924	2.35	0.0192
CS31	10.7976	2.4924	4.33	<.0001
CS32	1.045911	2.4924	0.42	0.6750
CS33	1.716594	2.4924	0.69	0.4915
CS34	4.260093	2.4924	1.71	0.0883
CS35	3.883198	2.4924	1.56	0.1202
CS36	7.993075	2.4924	3.21	0.0015
CS37	9.688993	2.4924	3.89	0.0001
CS38	2.70966	2.4924	1.09	0.2777
CS39	1.505326	2.4924	0.60	0.5463
CS40	13.81483	2.4924	5.54	<.0001

CS41	10.42481	2.4924	4.18	<.0001
CS42	10.77078	2.4924	4.32	<.0001
CS43	9.133912	2.4924	3.66	0.0003
CS44	1.385264	2.4924	0.56	0.5787
CS45	1.599566	2.4924	0.64	0.5215
CS46	0.62251	2.4924	0.25	0.8029
CS47	1.124756	2.4924	0.45	0.6521
CS48	0.88007	2.4924	0.35	0.7242
CS49	1.946659	2.6628	0.73	0.4653
CS50	4.665996	2.4924	1.87	0.0621
CS51	1.689892	2.6628	0.63	0.5261
CS52	5.285651	2.4924	2.12	0.0347
CS53	6.445055	2.8052	2.30	0.0222
CS54	0.405419	2.5652	0.16	0.8745
CS55	1.280461	2.4924	0.51	0.6078
CS56	5.479903	2.4924	2.20	0.0286
CS57	3.909796	2.4924	1.57	0.1177
CS58	-0.35226	2.4924	-0.14	0.8877
CS59	16.23978	2.8052	5.79	<.0001
Intercept	-0.12908	3.8560	-0.03	0.9733
Time	0.562459	0.1029	5.47	<.0001
Cooling Degree Days	0.001167	0.00163	0.72	0.4735
Heating Degree Days	-0.00016	0.000500	-0.32	0.7494

Table 3: Regression Results for the Effect of Aging on Chilled Water Consumption

b) Dependent Variable: Electricity per GSF

Variable	Estimate	Standard Error	t Value	Pr > t
CS1	11.24225	3.1537	3.56	0.0004
CS2	10.67439	3.1537	3.38	0.0008
CS3	13.16662	3.1537	4.17	<.0001
CS4	15.14619	3.1537	4.80	<.0001
CS5	42.70161	3.1537	13.54	<.0001
CS6	5.812696	3.1537	1.84	0.0658
CS7	35.26784	3.1537	11.18	<.0001
CS8	-1.39141	3.1537	-0.44	0.6592
CS9	34.35697	3.1537	10.89	<.0001
CS10	10.90218	3.1537	3.46	0.0006
CS11	9.554457	3.1537	3.03	0.0026
CS12	6.413472	3.1537	2.03	0.0424
CS13	10.477	3.1537	3.32	0.0009
CS14	7.642921	3.1537	2.42	0.0157
CS15	9.63675	4.0779	2.36	0.0184
CS16	-1.83323	4.0779	-0.45	0.6532
CS17	6.590108	3.1537	2.09	0.0371
CS18	8.785588	3.1537	2.79	0.0055
CS19	9.662821	3.1537	3.06	0.0023
CS20	23.85107	3.1537	7.56	<.0001
CS21	18.62491	3.1537	5.91	<.0001
CS22	6.966573	3.1537	2.21	0.0275
CS23	108.3127	3.1537	34.34	<.0001
CS24	10.65373	3.1537	3.38	0.0008
CS25	23.63206	3.1537	7.49	<.0001
CS26	20.49013	3.1537	6.50	<.0001
CS27	5.057982	4.0779	1.24	0.2153

CS28	2.290388	3.1537	0.73	0.4680
CS29	11.70701	3.1537	3.71	0.0002
CS30	5.76003	3.1537	1.83	0.0683
CS31	12.61461	3.1537	4.00	<.0001
CS32	13.6256	3.1537	4.32	<.0001
CS33	37.36017	3.1537	11.85	<.0001
CS34	8.767085	3.1537	2.78	0.0056
CS35	35.57098	3.1537	11.28	<.0001
CS36	1.196263	3.1537	0.38	0.7046
CS37	19.27447	3.1537	6.11	<.0001
CS38	43.48276	3.1537	13.79	<.0001
CS39	6.03265	3.1537	1.91	0.0562
CS40	-3.30002	3.7021	-0.89	0.3731
CS41	12.04614	3.1537	3.82	0.0001
CS42	12.48102	3.1537	3.96	<.0001
CS43	0.291853	3.1537	0.09	0.9263
CS44	5.877126	4.7390	1.24	0.2154
CS45	19.59919	3.1537	6.21	<.0001
CS46	30.65492	3.1537	9.72	<.0001
CS47	24.24724	3.1537	7.69	<.0001
CS48	14.75041	3.1537	4.68	<.0001
CS49	6.939184	3.1537	2.20	0.0282
CS50	12.98146	3.1537	4.12	<.0001
CS51	20.25149	3.1537	6.42	<.0001
CS52	24.6033	3.1537	7.80	<.0001
CS53	10.40594	3.1537	3.30	0.0010
CS54	-1.24604	3.4566	-0.36	0.7186
CS55	26.32035	3.1537	8.35	<.0001
CS56	3.84948	3.1537	1.22	0.2227
CS57	6.824995	3.1537	2.16	0.0308
CS58	-4.43291	3.7027	-1.20	0.2317
CS59	3.332467	3.1537	1.06	0.2911
CS60	7.616422	3.1537	2.42	0.0160
CS61	3.17629	3.1537	1.01	0.3143
CS62	2.160422	3.1537	0.69	0.4936
CS63	11.24796	3.1537	3.57	0.0004
CS64	5.862623	3.1537	1.86	0.0635
CS65	4.037998	3.2832	1.23	0.2192
CS66	-4.46023	3.1537	-1.41	0.1578
CS67	14.95334	3.1537	4.74	<.0001
CS68	9.879561	3.1537	3.13	0.0018
CS69	0.917973	3.1537	0.29	0.7711
CS70	-1.60112	3.1537	-0.51	0.6119
CS71	10.41291	3.2832	3.17	0.0016
CS72	1.177486	3.1537	0.37	0.7090
CS73	36.06271	3.1537	11.43	<.0001
CS74	12.7978	3.1537	4.06	<.0001
CS75	5.78581	3.1537	1.83	0.0670
CS76	29.03758	3.1537	9.21	<.0001
CS77	53.02555	3.1537	16.81	<.0001
CS78	20.26105	3.1537	6.42	<.0001
CS79	1.220325	3.2831	0.37	0.7102
CS80	1.675404	3.1537	0.53	0.5954
CS81	-0.5567	3.1537	-0.18	0.8599
CS82	8.909329	4.0779	2.18	0.0293
CS83	0.262534	3.1537	0.08	0.9337

CS84	15.23051	3.1537	4.83	<.0001
CS85	0.406071	3.1537	0.13	0.8976
CS86	3.622785	3.1537	1.15	0.2511
CS87	10.67596	3.1537	3.39	0.0008
CS88	-0.01426	3.1537	-0.00	0.9964
CS89	18.05546	3.1537	5.73	<.0001
CS90	3.227505	3.1537	1.02	0.3065
CS91	13.7568	3.1537	4.36	<.0001
CS92	9.686196	3.1537	3.07	0.0022
CS93	10.9319	3.1537	3.47	0.0006
CS94	4.860957	3.7027	1.31	0.1897
CS95	-0.94061	3.1537	-0.30	0.7656
CS96	-2.56889	3.1537	-0.81	0.4156
CS97	0.290659	3.1537	0.09	0.9266
CS98	-2.62249	3.1537	-0.83	0.4060
CS99	6.026005	3.1537	1.91	0.0565
CS100	1.583125	3.1537	0.50	0.6159
CS101	5.763337	3.1537	1.83	0.0681
CS102	2.913542	3.1537	0.92	0.3559
CS103	1.030993	3.1537	0.33	0.7438
CS104	5.889736	3.7027	1.59	0.1122
CS105	1.710406	3.1537	0.54	0.5878
CS106	2.50427	3.1537	0.79	0.4275
CS107	0.612331	3.1537	0.19	0.8461
CS108	-4.08382	4.7390	-0.86	0.3892
CS109	10.84632	3.1537	3.44	0.0006
CS110	70.01479	3.1537	22.20	<.0001
CS111	15.35357	3.1537	4.87	<.0001
Intercept	2.944208	4.1628	0.71	0.4797
Time	0.460556	0.1119	4.12	<.0001
Heating Degree Days	0.000309	0.000546	0.57	0.5719
Cooling Degree Days	-0.00037	0.00177	-0.21	0.8369

Table 4: Regression Results for the Effect of Aging on Electricity Consumption

c) Dependent Variable: Steam per GSF

Variable	Estimate	Standard Error	t Value	Pr > t
CS1	0.018101	0.0195	0.93	0.3531
CS2	0.007152	0.0195	0.37	0.7136
CS3	0.003032	0.0195	0.16	0.8763
CS4	0.007852	0.0195	0.40	0.6869
CS5	0.119792	0.0195	6.15	<.0001
CS6	0.006201	0.0195	0.32	0.7503
CS7	0.204488	0.0195	10.50	<.0001
CS8	0.046779	0.0195	2.40	0.0167
CS9	0.135924	0.0195	6.98	<.0001
CS10	0.007358	0.0195	0.38	0.7057
CS11	-0.03095	0.0195	-1.59	0.1127
CS12	0.00924	0.0195	0.47	0.6354
CS13	0.007777	0.0195	0.40	0.6898
CS14	0.016357	0.0195	0.84	0.4013
CS15	-0.04752	0.0252	-1.89	0.0599
CS16	0.010594	0.0195	0.54	0.5867
CS17	0.019197	0.0195	0.99	0.3247
CS18	0.009668	0.0195	0.50	0.6197

CS19	-0.03392	0.0195	-1.74	0.0821
CS20	0.03429	0.0195	1.76	0.0789
CS21	-0.01686	0.0195	-0.87	0.3870
CS22	0.578426	0.0195	29.71	<.0001
CS23	0.01783	0.0195	0.92	0.3603
CS24	0.017021	0.0195	0.87	0.3825
CS25	0.015879	0.0195	0.82	0.4152
CS26	0.026601	0.0252	1.06	0.2915
CS27	0.070576	0.0195	3.62	0.0003
CS28	0.017349	0.0195	0.89	0.3734
CS29	-0.00206	0.0195	-0.11	0.9156
CS30	0.002829	0.0195	0.15	0.8845
CS31	0.214397	0.0195	11.01	<.0001
CS32	0.034909	0.0195	1.79	0.0737
CS33	0.048061	0.0195	2.47	0.0139
CS34	-0.0057	0.0195	-0.29	0.7697
CS35	0.063785	0.0195	3.28	0.0011
CS36	0.133321	0.0195	6.85	<.0001
CS37	0.020688	0.0195	1.06	0.2886
CS38	0.018079	0.0195	0.93	0.3536
CS39	0.007527	0.0195	0.39	0.6992
CS40	-0.00273	0.0195	-0.14	0.8888
CS41	0.013028	0.0293	0.44	0.6565
CS42	0.007197	0.0195	0.37	0.7119
CS43	0.214486	0.0195	11.02	<.0001
CS44	0.096246	0.0195	4.94	<.0001
CS45	0.029084	0.0195	1.49	0.1359
CS46	-0.00378	0.0195	-0.19	0.8464
CS47	-0.02111	0.0195	-1.08	0.2788
CS48	-0.03161	0.0195	-1.62	0.1052
CS49	-0.04792	0.0195	-2.46	0.0142
CS50	-0.02726	0.0195	-1.40	0.1622
CS51	-0.04451	0.0195	-2.29	0.0227
CS52	-0.00497	0.0195	-0.26	0.7987
CS53	0.033944	0.0195	1.74	0.0820
CS54	-0.00507	0.0195	-0.26	0.7946
CS55	0.044338	0.0195	2.28	0.0232
CS56	-0.03934	0.0195	-2.02	0.0439
CS57	0.007541	0.0195	0.39	0.6987
CS58	0.007603	0.0195	0.39	0.6964
CS59	0.007362	0.0195	0.38	0.7055
CS60	-0.02205	0.0203	-1.09	0.2773
CS61	-0.00044	0.0195	-0.02	0.9818
CS62	-0.00033	0.0195	-0.02	0.9864
CS63	0.003586	0.0195	0.18	0.8540
CS64	-0.0024	0.0195	-0.12	0.9019
CS65	-0.00031	0.0195	-0.02	0.9873
CS66	-0.01053	0.0195	-0.54	0.5890
CS67	-0.00094	0.0195	-0.05	0.9616
CS68	0.006664	0.0195	0.34	0.7323
CS69	0.00554	0.0195	0.28	0.7761
CS70	0.003203	0.0195	0.16	0.8694
CS71	0.138563	0.0229	6.06	<.0001
CS72	-0.00034	0.0195	-0.02	0.9862
CS73	-0.00035	0.0195	-0.02	0.9855
CS74	-0.00035	0.0195	-0.02	0.9856

CS75	-0.00088	0.0195	-0.05	0.9640
CS76	-0.00023	0.0195	-0.01	0.9905
CS77	-0.00035	0.0195	-0.02	0.9856
CS78	0.004769	0.0229	0.21	0.8349
CS79	-0.00034	0.0195	-0.02	0.9861
Intercept	-0.03386	0.0289	-1.17	0.2425
Time	0.005818	0.000802	7.25	<.0001
Heating Degree Days	0.000016	3.952E-6	4.02	<.0001
Cooling Degree Days	2.961E-6	0.000013	0.23	0.8178

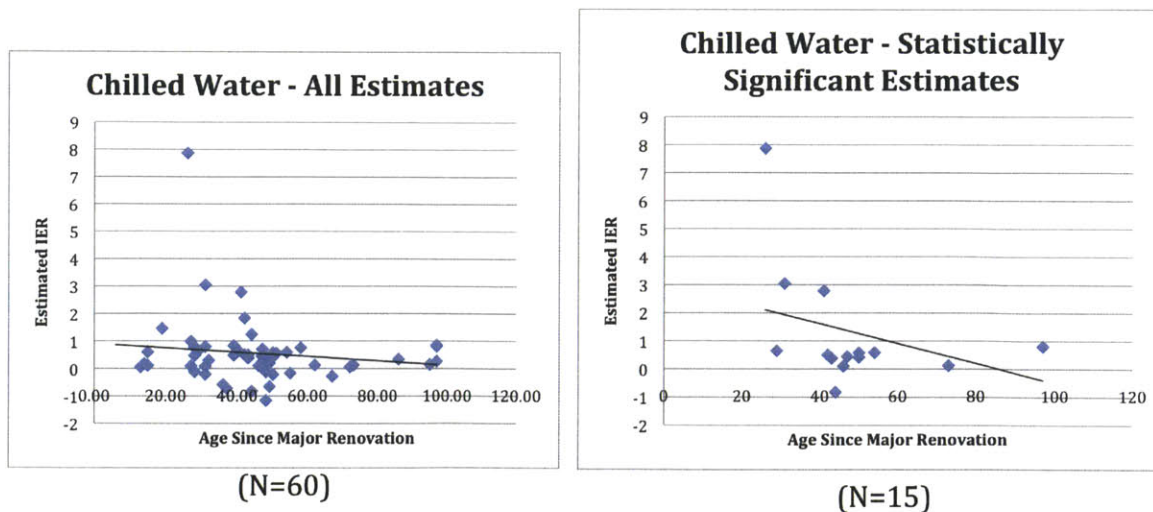
Table 5: Regression Results for the Effect of Aging on Steam Consumption

Estimating τ and E^* :

As described in the main text, we model the growth in building energy requirements using an exponential form:

$$IER_j = \frac{dE_j}{dt} = \frac{(E_j^* - E_j)}{\tau_j} \quad (6)$$

We use the data on building energy consumption to estimate the parameters τ and E^* for each of the three energy types. To begin, we run individual regressions for each building with time again as an independent variable. We then plot the time trend estimate for each building against the age of that building (since the last major renovation). For the functional form above to be a good representation, we expect to see a lower rate of growth in energy requirements for older buildings. (According to our functional form, as buildings age, they approach the maximum energy requirements E^* , increasing at a decreasing rate.) Plots are shown below:



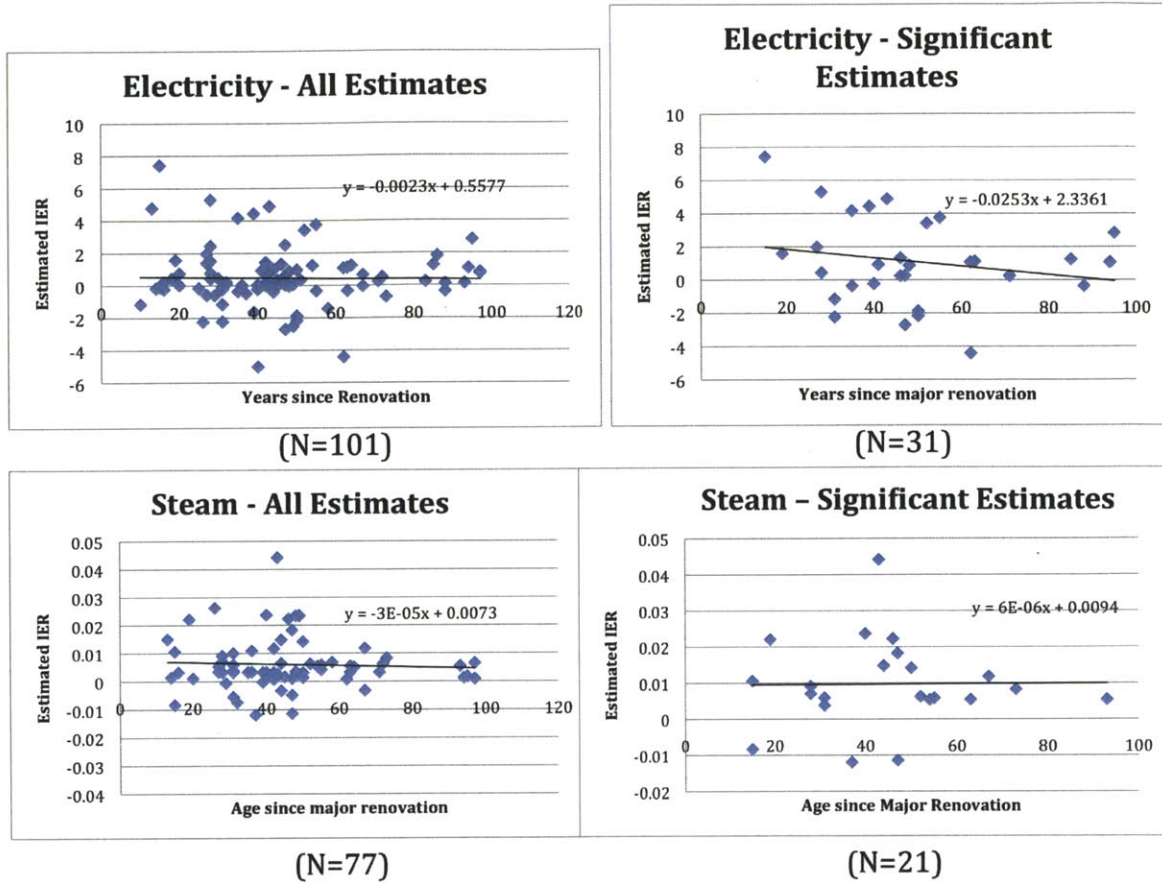


Figure 2: Plots of building age against regression estimates for the time trend (increase in energy requirements)

We next rewrite equation (6) to express the energy requirements as a function of time:

$$E_t = E^* - (E^* - E_0)e^{-t/\tau} \quad (7)$$

Taking the derivative, and then the logarithm of each side, we get a functional form that we can use to estimate tau:

$$\frac{dE}{dt} \approx IER = (E^* - E_0)e^{-t/\tau} \cdot \frac{1}{\tau} \quad (8)$$

$$\ln(IER) = \ln\left(\frac{E^* - E_0}{\tau}\right) - \frac{t}{\tau} \quad (9)$$

We use the individual building time trend regression estimates for the time trend as IER. We then regress IER against building age (t), and use the estimate for the slope to calculate tau. The model produces a statistically significant result for steam, but not for chilled water or electricity. Results are shown in Table 6.

	b estimate (standard error)	Tau = -1/b
Chilled Water	-0.00451 (.00672)	222.2 years
Electricity	-0.000584 (.0087)	1712 years
Steam	-0.00993* (0.00576)	100.7 years

*Table 6: Regression Results for the Model $\ln(ier) = a + b * \text{building age}$*

Given the failure to fit a good model for chilled water and electricity, we attempt a second approach. We place buildings into 5 “buckets” based on their age, using 20-year increments, and run a separate panel regression to determine an estimate of IER for each bucket. We then repeat the analysis above. IER estimates are shown in Table 7, and plotted in Figure 3. Regressing $\log(\text{IER})$ against age again gives estimates for tau of 37 years for chilled water, 552 years for electricity, and 117 years for steam. Due to the small number of data points in the buckets approach, these estimates are not significant. Nonetheless, we use the estimates for CW and electricity from the buckets approach, and the estimate from above for steam.

Age Bucket	Chilled Water		Electricity		Steam	
	IER Estimate	N	IER Estimate	N	IER Estimate	N
0-20	.579* (.16)	9	1.54* (.4)	16	.007* (.003)	11
21-40	.91* (.24)	17	.21 (.24)	30	.0046* (.0013)	22
41-60	.39* (.15)	23	.4* (.15)	34	.008* (.0013)	29
61-80	.005 (.11)	4	-.07 (.47)	10	.0045* (.0009)	9
81-100	.53* (.24)	6	.8* (.15)	12	.003* (.0009)	7

Table 7: IER Estimates for age buckets (smaller Ns for CW and Steam are due to the fact that not all buildings use CW and steam).

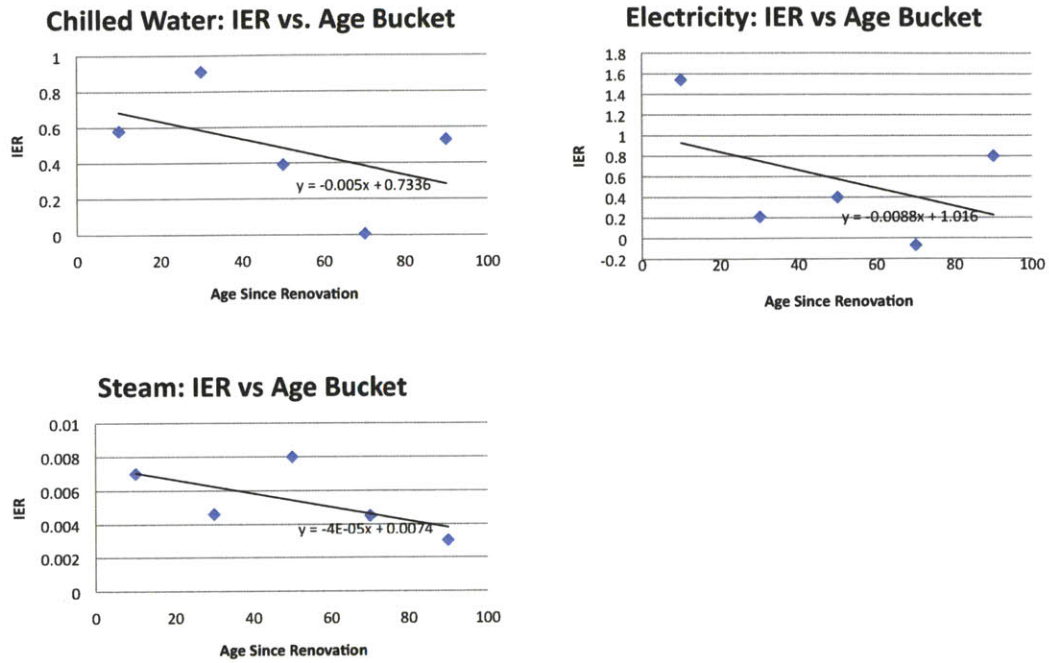


Figure 3: Plots of Building Age against the Estimated Increase in Energy Requirements (IER) for age buckets.

We next use the estimates for tau obtained above to obtain values for E^* . To do so, we use the original time trends from the full panel regressions described above. Specifically, we assume that the regression equation represents a linear approximation of the exponential curve around an operating point.

$$E(t) = a + bt + \text{Building Fixed Effects} + \text{Degree Day Effects} \quad (10)$$

$$b = \frac{(E^* - E_0)}{\tau}, \quad a = E_0$$

The slope of the regression equation is equal to the derivative of our assumed exponential form at the operating point. We then use the estimates for b and tau (determined above) to solve for E^* . Table 8 shows the final parameters used in the model.

	τ (years)	E_{2005}	E^*	E_0	Potential E Saved	E_{2000}
Chilled Water (Ton-hrs/yr/gsf)	37	7.48	20.79	3.35	4.129 (55%)	5.94
Electricity (Kwh/yr/gsf)	550	18.58	253.55	14.27	4.311 (23%)	17.83
Steam (Klb/yr/gsf)	116	0.119	0.675	0.0695	0.050 (41%)	.095

Table 8: Final parameters used for the energy model

Conceptually, these parameters have the following meaning. The energy requirements of buildings are assumed to grow at a decreasing rate, following an exponential goal-seeking structure (Figure 4 and Equation 8 in the main text). Tau is the time constant and E^* is the maximum energy requirements towards which actual energy usage approaches. We can see that E^* is larger than the actual value at the start of the simulation, E_{2005} . To calculate E_0 , we assume that 10 years of savings are available using the assumed formula. Conceptually, E_0 is the minimum energy usage of buildings if all systems were renewed and defects removed. In the table, we compare E_0 to E_{2000} (the earliest year of data) for point of reference. E_0 gives potential savings of 55% for chilled water, 23% for electricity, and 41% for steam. These savings represent the reduction that would be achieved if every defect were repaired and every building system that “needs renewal” is renewed.

Allocating Potential Energy Savings Among Items

Given potential energy savings, we next must allocate potential savings among renewal items and defect categories. Table 9 (based on expert interviews) shows how potential savings are allocated among categories. For example, 25% of chilled water savings can be realized by fixing or renewing exterior structures (e.g. repairing windows), and the remaining 75% can be realized through improvements to HVAC systems. We assume that 33% of electricity savings are not related to maintenance at all.

	CW	Electricity	Steam
Exterior Structures	25%	0	25%
Interior Structures	0	0	0
Plumbing	0	0	0

HVAC	75%	33%	75%
Electrical	0	33%	0
Not Renewal Related (eg. Plug loads)	0	33%	0

Table 9: Allocating Potential Energy Savings among building system categories

Potential savings within each category are then apportioned among individual items proportional to the renewal cost.

Implementing a Proactive Investment

The majority of model runs contain a proactive investment in maintenance. Below we describe exactly how that investment is implemented.

In simplest terms, the proactive investment can be described as a step increase in the capacity of the maintenance organization, measured in hours per year. We transform a desired dollar amount to hours by dividing by the average productivity and cost per work order. The work capacity then becomes the actual staff level plus an additional amount. Immediately, the added capacity causes the maintenance organization to complete more existing work orders and open new proactive work orders according to the resources that are available.

The time paths of the various investments described in the main text are shown in the figure below:

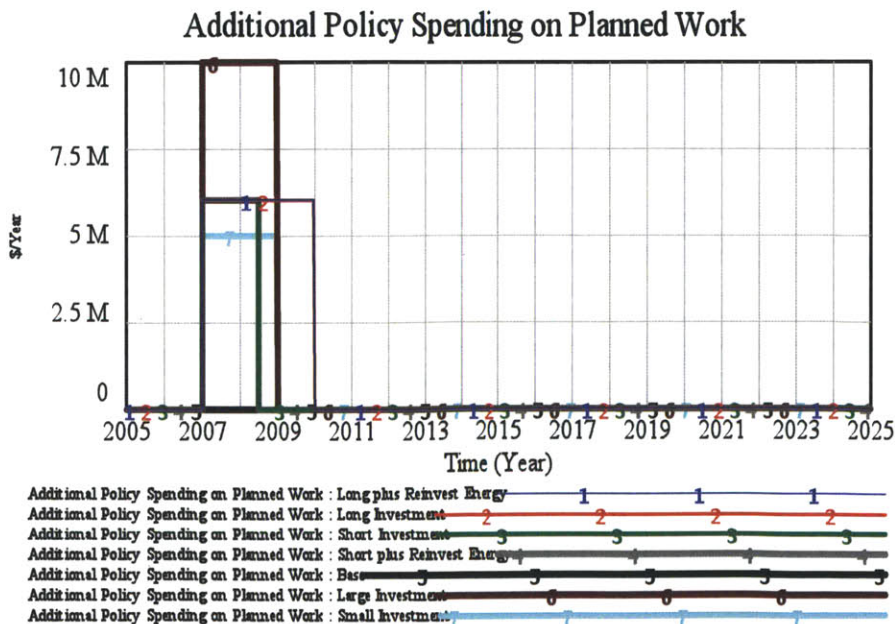


Figure 4: Time paths of investments for model runs shown in the paper

Reinvesting Energy Savings

For runs where energy savings are reinvested, we model reinvestment through the maintenance budget. Dollar savings are added to the budget, which drives hiring, which in turn drives capacity and opened work orders. Savings are calculated by comparing energy spending to energy spending in a base run.

Financial Calculations

For each policy run, we compute a NPV for the investment, compared to the base run. Financial calculations are performed as follows:

First, a rate of spending is calculated continuously, based on labor hours worked (with a premium for overtime), materials cost per work order completed, and fixed costs. Energy spending is calculated by multiplying energy requirements by the price of energy.

We next accumulate spending in a stock, discounting over time at an assumed interest rate of 5%. At the end of the simulation, we calculate the NPV of the investment by subtracting the accumulated discounted spending from the discounted accumulated spending in the base run. We also take the final rate of spending at the end of the simulation (once again compared to the base run) and project the NPV of savings using the same formula shown above in Equation 5 of the appendix.

We calculate NPV in this manner for the case of maintenance spending along, and maintenance spending plus energy spending.

We also considered alternate ways to value investments, including ROI. However, ROI requires defining a fixed “investment” and fixed “savings” – calculations that are not always meaningful given the specific nature of the investment here. For example it is hard to know from what base “savings” should be measured, given the many endogenous relationships between variables in the model. We conclude that alternate measures are less accurate and meaningful than the NPV calculation.

Diagrams of Model Sectors

Below we provide diagrams and explanations of the main model sectors:

Building Renewal Sector

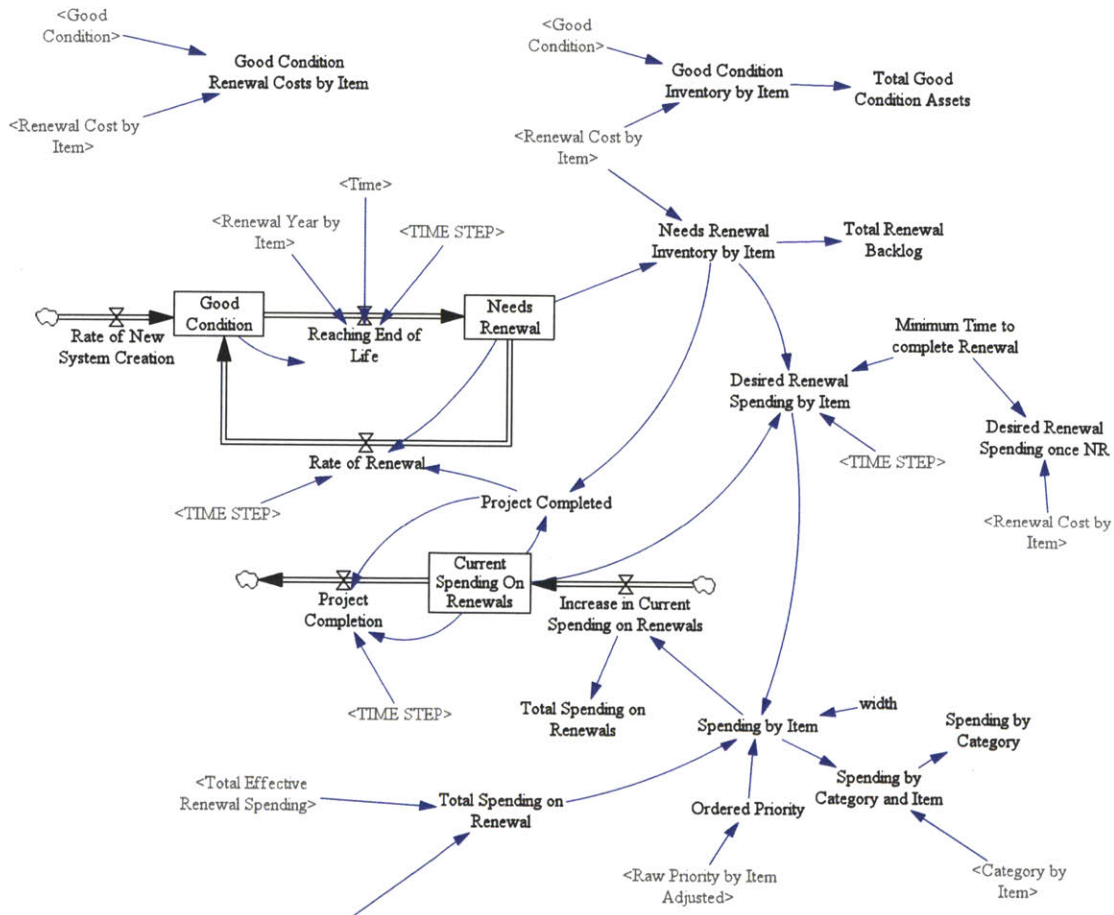


Figure 5: Model Diagram for the Building Renewal Sector

Figure 5 shows the model diagram for the building renewal sector. As described in the main text, building systems are classified in one of two conditions: “good condition,” or “needs renewal,” according to an engineering database of the entire campus. In this sector of the model, each individual system is modeled individually in discrete time, using subscripts in Vensim. For example, if the fire protection system for building A reaches the end of its recommended life in 2016, the associated item will age from the GC stock to the NR stock at the beginning of 2016. In addition, each item has an associated renewal cost, also provided by the engineering database. The variable “good condition inventory by item” stores the cost for each item, and the variable “total good condition assets” sums up the total value of these assets.

The “desired renewal spending by item” captures the desired rate of spending to renew an item. This amount reflects the minimum amount of time needed to complete the renewal, along with any spending that has occurred already. We assume that renewals can be completed in one year. (Thus, spending is divided evenly over the course of one year, assuming funds are available). The stock “Current spending on renewals” accumulates all spending that has occurred for a given item: when “current

spending” matches the “renewal cost” for an item, the item is moved from the NR stock to the GC stock and the “current spending” stock is drained.

Total spending is divided amongst individual items according to a prioritization scheme, discussed below. The variable “spending by item” uses an algorithm to allocate total renewal dollars among the items. Funds are first allocated to the highest priority item until that item’s demand is met, then to the second priority item, and then to the third, and so on until all funds are exhausted. The variable “spending by category” sums up spending across the categories of building systems.

Prioritization of Renewal Items

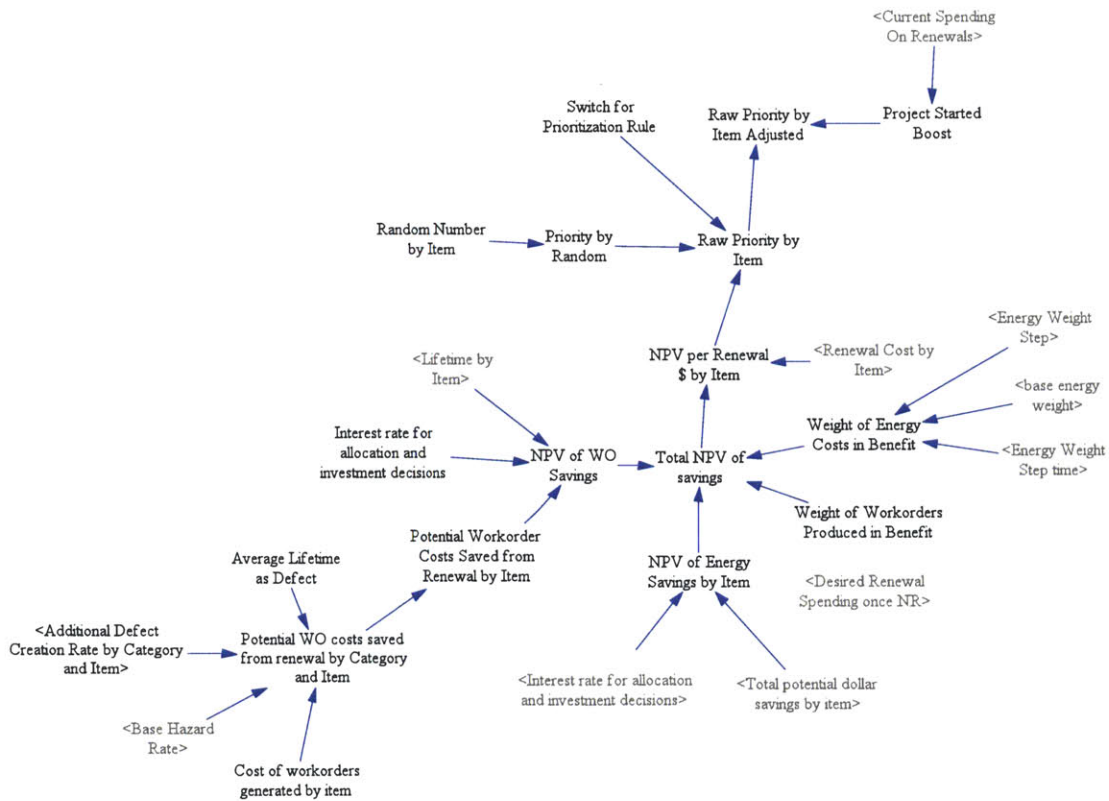


Figure 6: Model Diagram for the Prioritization of Renewal Items

Figure 6 shows the model structure for the prioritization among renewal items. The variable “Raw Priority by Item Adjusted” is a numeric value assigned to each item that is used to create a rank order. The “project started boost” adds a large amount to projects that have already received funding, to ensure that such items continue to receive funding until they are complete. (This applies to projects that are only partially funded during one year due to insufficient funds).

The model includes two different prioritization schemes. The first is a random prioritization scheme in which items are assigned a random number. The second (the

default used in all runs shown in the paper) assigns priority according to the NPV of renewal per dollar of renewal cost. The cost of renewal for an item is given by the engineering database. The NPV of renewal includes both savings in reduced maintenance workorders, and energy savings.

The potential energy savings per item are calculated as described below. The maintenance savings are calculated using the difference between the hazard rates for NR and for GC items. (The model is parameterized such that NR items generate defects at a higher rate). We multiply the difference in the rate of defects created, by the average lifetime of a defect, by the rate of workorders and cost of workorders created per defect. The difference is then accumulated over the lifetime of the renewal, with future values discounted. In other words, if a renewal has a lifetime of 15 years, we assume savings for 15 years. Energy and workorder savings are then weighted to give a total value. (For example, the model could be parameterized such that decisions are based on workorder savings only).

Energy Requirements from Buildings

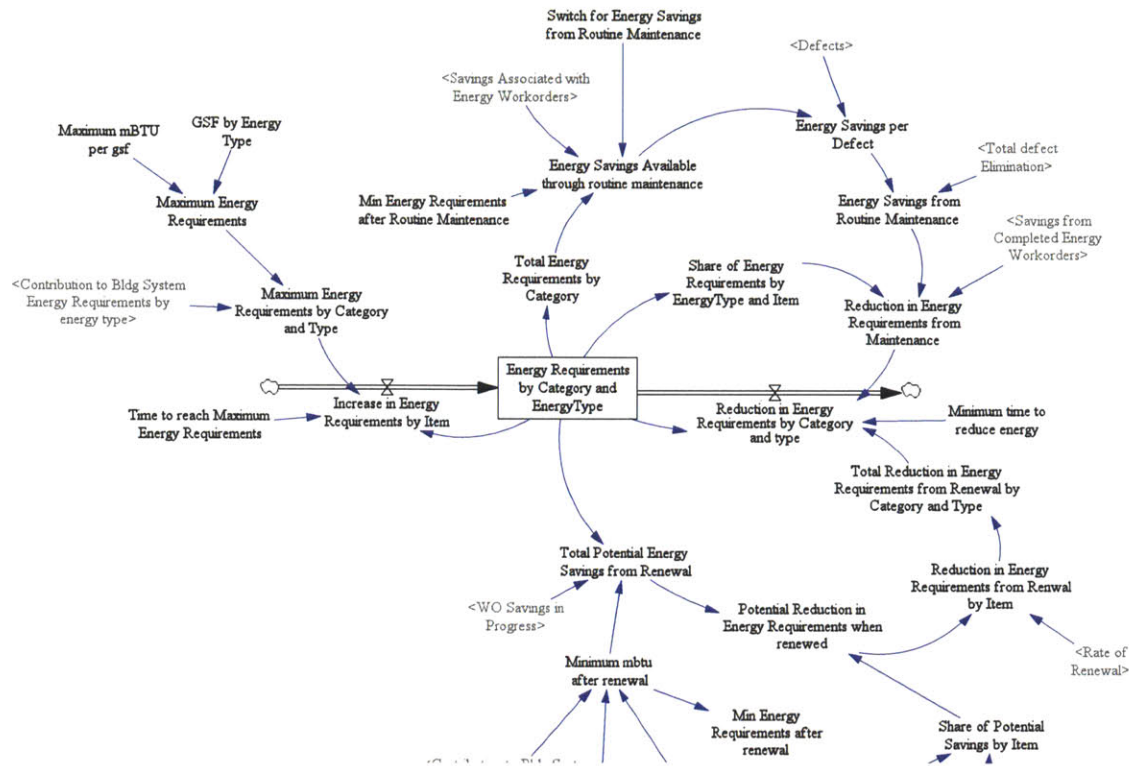


Figure 7: Model Diagram for Energy Requirements from Buildings

Figure 7 shows the model structure for the Energy Requirements from buildings. The stock “Energy Requirements by Category and EnergyType” gives the total rate of energy consumption, aggregated across building system categories and across the three types of energy consumption (steam, chilled water, and electricity). The formulation for the “Increase in Energy Requirements” is described in detail above. The formulation for “Reductions in Energy Requirements” includes reductions that occur through two channels: through maintenance (defect elimination), and through renewal.

Reductions in energy requirements through renewals are shown in the bottom part of the diagram. The variable “Minimum mbtu after renewal” is the minimum consumption assuming that all renewals are completed. We calculate a minimum value first for each energy type, and then apportion potential savings between categories as described above. Potential savings are the difference between the minimum and the current consumption. Potential savings are then divided among individual NR items according to the variable “share of potential savings by item.” The share is calculated by considering several factors. First, we use the expert elicitation process described in the main text to classify the relative contribution of groups of items within each category, on a 0-1 scale. For example, within the exterior structures category, “windows” are given a weight of 1 whereas balcony railings are given a zero weight. Second, we consider the renewal cost. Items with a higher renewal cost are assumed to contribute more to potential energy savings. This assumption has limitations. However, by including cost

we reflect the fact that larger and more complex systems are likely housed in larger buildings and therefore contribute more to energy savings. Finally, item weights include a small random component to capture heterogeneity across items. The three components (cost, expert judgment, and random) are then multiplied, giving a value for each item. We then use the value to calculate a market share for each item.

Equipment Defects and Elimination

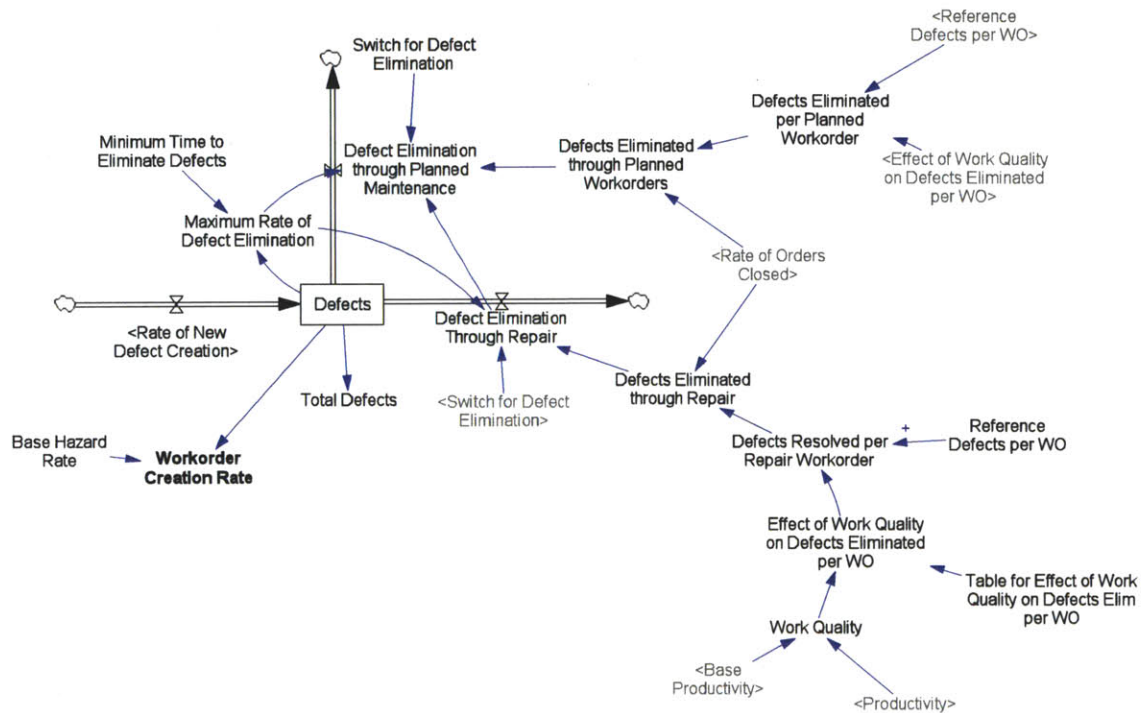
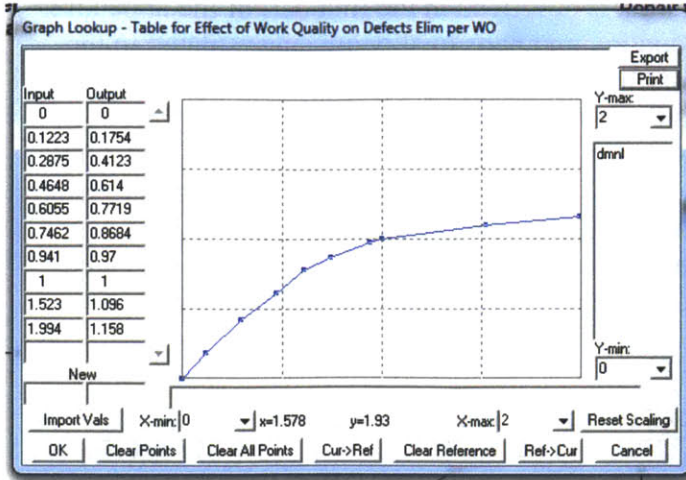


Figure 8: Model Diagram for Equipment Defects and Elimination

Equipment defects are modeled as shown in Figure 8. The rate of new defect creation is the inflow to the stock, and is described below. The workorder creation rate is the number of defects times the hazard rate (workorders/defect/year).

Defects are eliminated through two channels: repair work and planned work. Repair work constitutes responses to breakdowns. The variable “Defects eliminated through repair” is the number of closed workorders multiplied by the number of defects resolved per repair workorder. In turn, “defects resolved per workorder” is a function of work quality. When quality is high, defects eliminated per workorder is higher. As quality slips and workers cut corners, fewer defects are eliminated for each workorder. The effect of quality on defects per work order is modeled using a nonlinear table function (shown below). The x axis is work quality (defined as reference productivity/productivity), and the y axis is the effect on defect elimination. As quality increases from a reference point of (1,1), the rate of defect elimination increases slightly. Likewise, the rate of defect elimination declines slightly initially as quality deteriorates, before declining more rapidly as quality approaches 0.



Defect Creation

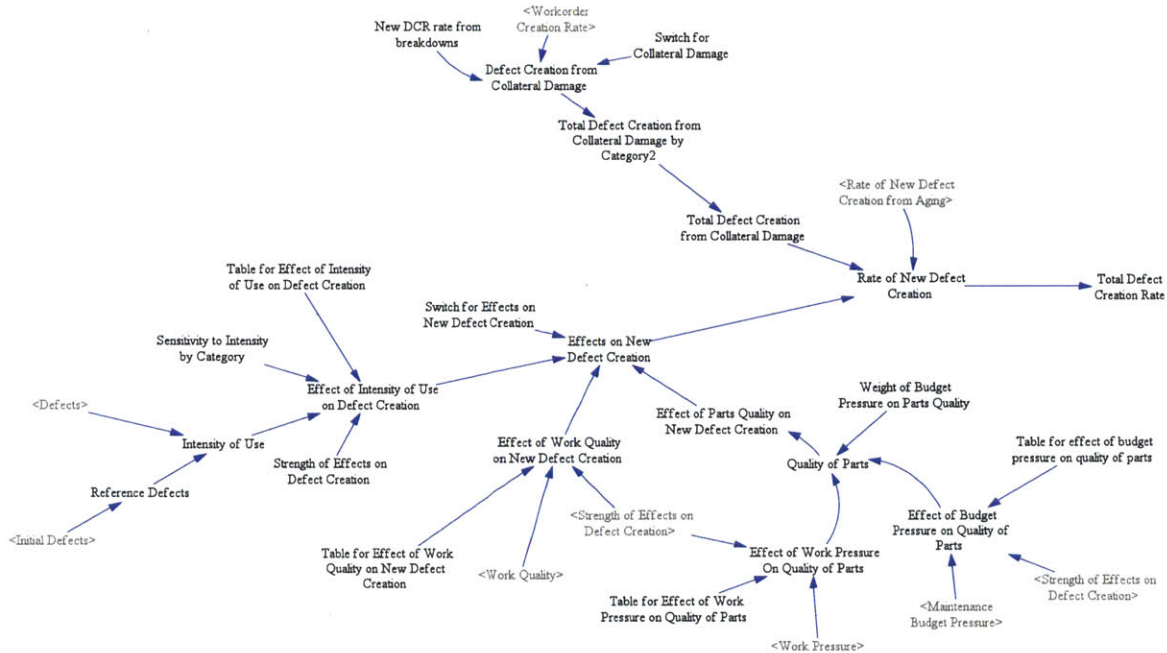
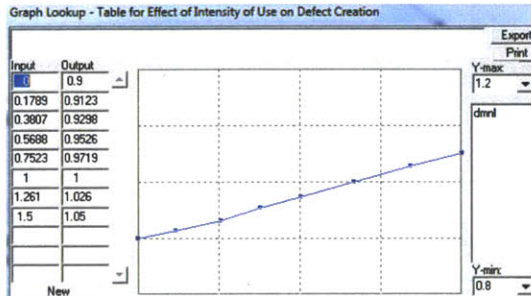


Figure 9: Model Diagram for Defect Creation

The formulation for defect creation is presented in equation 7 in the main text. Figure 9 provides more detail. The “Rate of New Defect Creation from Aging” is the base rate of defect creation, as determined by the condition of the campus (the extent to which building systems need renewal). The base rate rises as more items enter the needs renewal stock, as described above. In addition, the rate of defect creation is influenced by collateral damage, intensity of use, work quality, and parts quality. All of these effects are illustrated in the causal loop diagram shown in Figure 2 in the main text.

The collateral damage formulation is described in the first part of the appendix. The effects of intensity of use, work quality, and parts quality are encapsulated in the variable “Effects on New Defect Creation.”

Intensity of Use is modeled as the Number of Defects relative to a reference number of defects. For a fixed number of building systems, a larger stock of existing defects increases the chance that new defects will emerge, as systems become strained or as cracks and leaks spread. The nonlinear function shown below describes this relationship. The x-axis is intensity of use, and the y-axis is the effect on new defect creation. (The effect saturates and becomes flat beyond the bounds of the graph).



The effects of work quality and parts quality are formulated in a similar manner. Work quality is a function of productivity - we assume that as productivity increases in response to work pressure, quality declines. Parts quality is a function of both work pressure and budget pressure. High budget pressure leads to inferior parts; high work pressure reduces the time available to locate parts that are the best match.

The variable “Strength of Effects on Defect Creation” moderates all three relationships by adjusting the slope of the functional relationships. A stronger effect implies a higher slope. A stronger effect for these relationships increases the strength of associated positive feedback loops shown in Figure 2 in the main text. We test the sensitivity of results to the strength of positive feedback in the main text.

Work Order Backlog

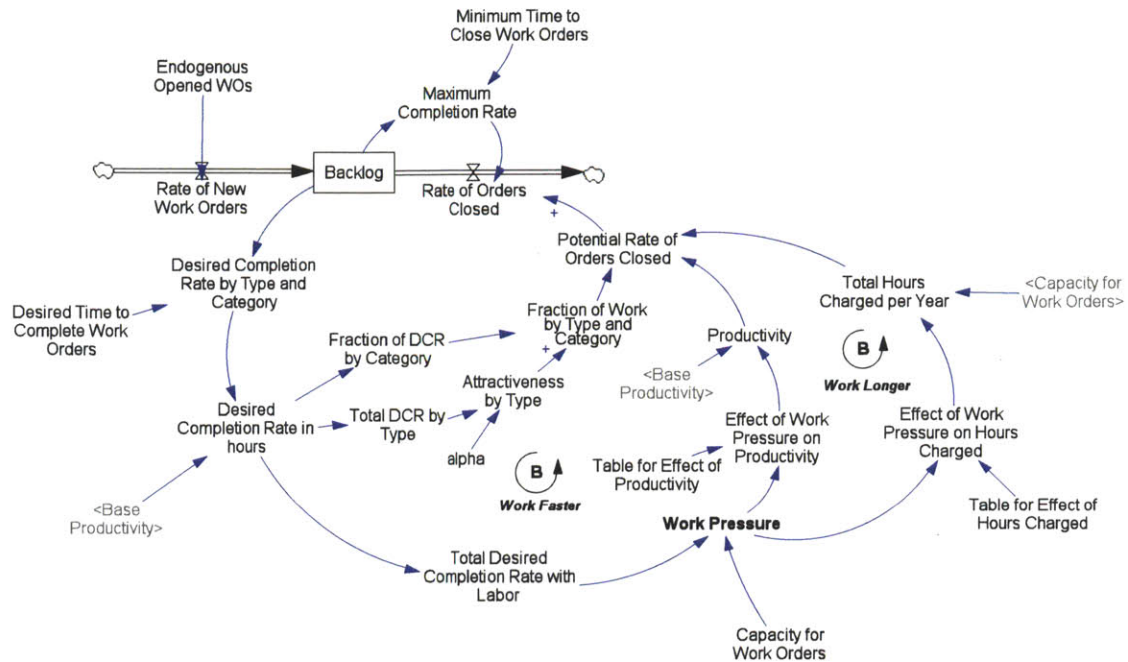


Figure 10: Model Diagram for Work Order Backlog and Completion

Figure 10 shows the full model diagram for the work order backlog and completion structure. (Figure 1 in the main text provides a simplified view). New work orders are opened and accumulated in a backlog, until they are closed. The model is disaggregated by building system category and again by type of work order (proactive or reactive). We first calculate the desired completion rate (workorders per week) for each type and category of work order by dividing the backlog by the desired completion time. We then calculate desired completion rate in hours by dividing by the base productivity, and sum over all types and categories to get the total desired completion rate. The total desired completion rate (hours/week) is then compared to work capacity (hours/week) to determine “work pressure.”

The relationship between work pressure and productivity and between work pressure and hours worked is described in the main text. We used actual work order data to estimate these relationships. Data used included weekly data on work orders opened, work orders closed, backlog, hours worked and productivity. First, we calculated the “work pressure” for each week using data for backlog and using estimates for the ‘desired completion time’ obtained from interviews and written documents. We then regressed work pressure against productivity and work pressure against total hours worked, using the functional form described in the text. A graphical non-linear function is used in the model (e.g. “table for effect of productivity”) to capture these estimates, following the procedure outlined in Sterman (2000), chapter 14, pg. 570-571. The function is linear around an operating point, with a slope determined by the regression estimate. (The operating point is the point at which work pressure =1 – that is, where capacity exactly

matches the desired completion rate. When work pressure =1, productivity is set to equal “base productivity.”)

The “fraction of work by type and category” is calculated using the logit choice model, as described in the main text. We allocate among categories using a proportional model, and then allocate between proactive and reactive work using the logit model. (The variable “attractiveness by type” considers the total desired completion rate for proactive and reactive, while the variable “fraction of dcr by category” calculates the fraction for each category of building system).

Finally, structure is included to ensure that work orders cannot be completed beyond the maximum that are available in the backlog. The variable “maximum completion rate” gives the maximum rate at which work orders can be completed. The actual rate of orders completed is the minimum of this maximum rate and the amount that capacity will support.

Maintenance Staffing

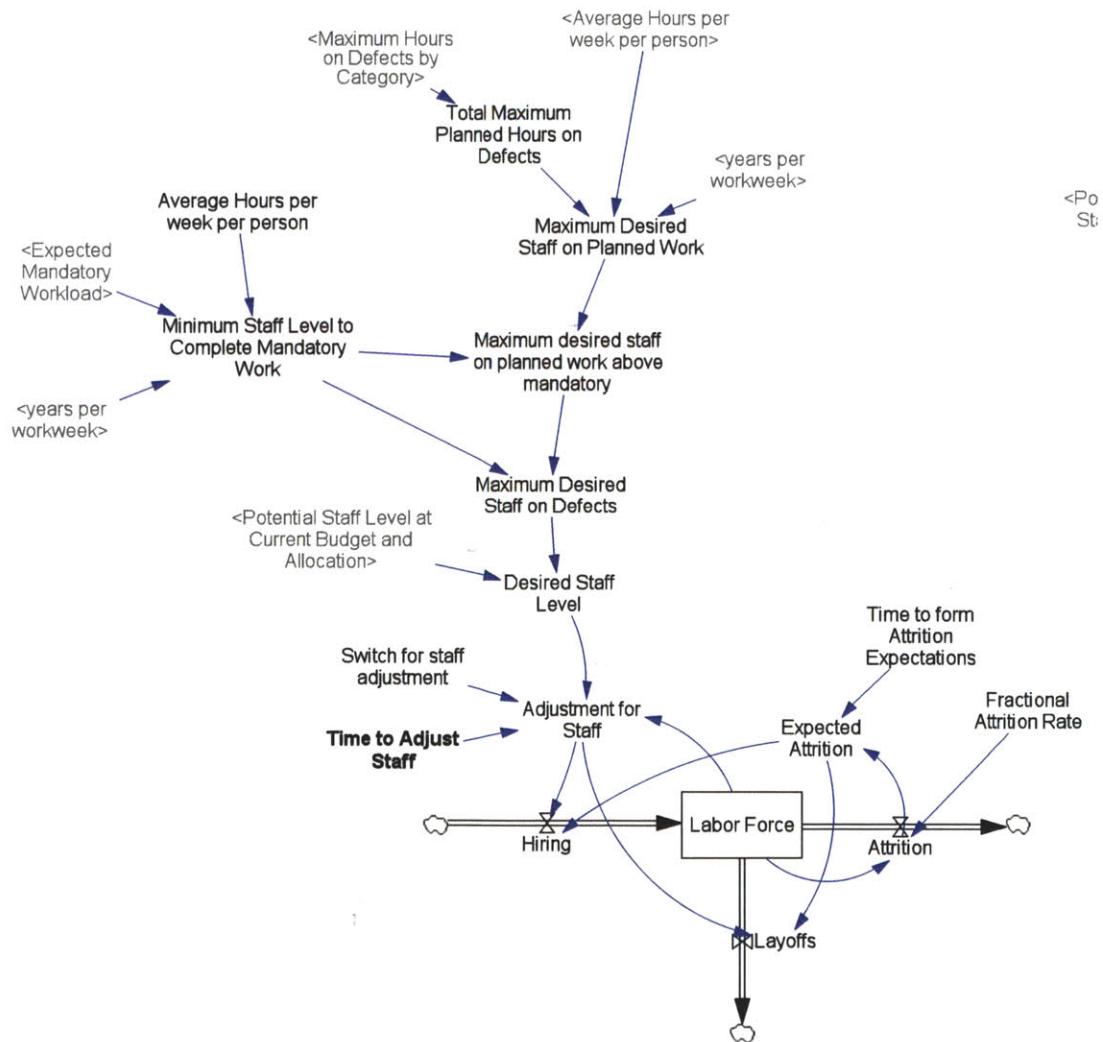


Figure 11: Model Diagram for Maintenance Staffing

Figure 11 shows the model structure for maintenance staffing. The level of the maintenance staff determines the volume of work (reactive and proactive) that can be completed. In turn, staff is hired and laid off endogenously according to work demands.

The variable “Desired Staff Level” determines staff level adjustment. If desired staff is greater than the “Labor Force,” “Adjustment for Staff” is positive and hiring occurs. If adjustment for staff is negative, layoffs occur. Hiring and layoffs also account for expected attrition.

The desired staff level is the minimum of two quantities: the staff level that can be supported given the current budget, and the staff level required to complete all available work (including all possible proactive work). The formulation ensures that gains from initial investment are not harvested but instead are reinvested. That is, even as the required reactive work declines due to proactive investment, the budget and staff level are not cut as long as proactive work remains. Staff level is reduced only when available proactive work no longer exists. (The variable “maximum desired staff on defects” is the staff level necessary to complete all proactive and reactive work). At the start of the simulation, the maximum desired staff is much greater than the staff level that the budget will support, due to the large stock of defects. In some of the simulation runs with large investments, only near the end of the runs does maximum desired staff begin to fall to the extent that layoffs become possible.

In turn, the variable “potential staff level at current budget and allocation” is set based on the budget. (The budget structure is shown below). The potential staff level is the number of staff that the current budget can support, given the expected composition of work and cost per work order. When a large fraction of work is proactive, because the materials cost of a proactive work order is less than the cost of a reactive work order, a given budget can support a greater number of work orders and thus a greater staff level. In turn, when a large fraction of work is reactive, fewer staff can be supported for the same budget.

The “maximum desired staff on defects” is the total staff necessary to complete all proactive and reactive work. This is the sum of staff necessary to complete “mandatory work” and staff necessary to complete non-mandatory (or discretionary) work. Mandatory work includes all reactive work and a small amount of proactive work that is set as a policy. (Even when the volume of reactive work is extremely high, the organization still initiates some proactive work orders, such as preventive maintenance checks on high priority equipment). Discretionary work is all remaining proactive work, defined as the stock of defects divided by the minimum time to find and correct defects.

Maintenance Budget

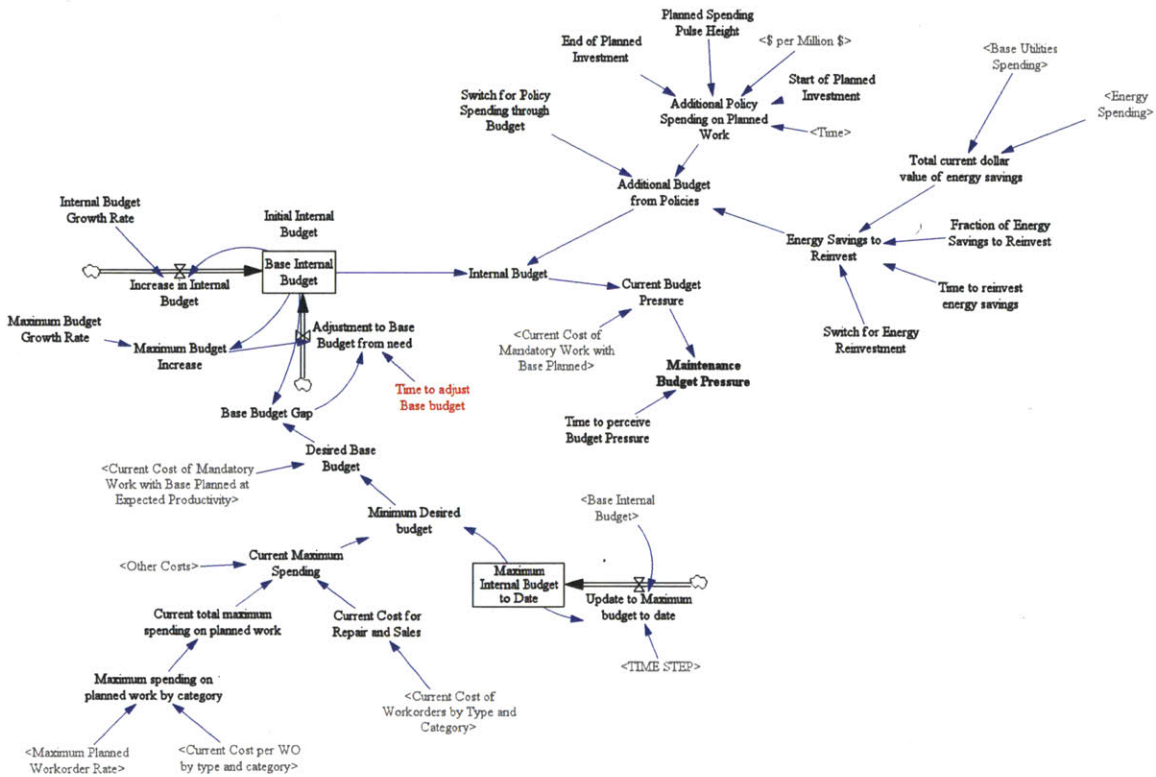


Figure 12: Model Diagram for the Maintenance Budget

The maintenance budget structure goes hand in hand with the staffing structure. Figure 12 shows the structure used. The variable “internal budget” is used as the output that informs staffing decisions. The internal budget is a base budget plus an additional budget from policies. The additional budget from policies includes additional resources added as a policy, plus energy savings that are reinvested. “Budget Pressure” is defined as the current cost of mandatory work (reactive work plus a small amount of planned work that the organization cannot omit) divided by the current budget.

The base internal budget is determined as follows. Conceptually, the budget is set according to several criteria. First, if the cost of mandatory work rises, the budget will rise to accommodate the increase, with a lag. Second, the budget cannot be reduced as long as proactive work still remains. The variable “desired base budget” captures both of these criteria. The “desired base budget” is the maximum of required mandatory spending and a minimum budget floor. If mandatory spending rises above the floor, the desired budget increases. If mandatory spending falls (for example, when a proactive investment reduces the volume of reactive work), the desired budget remains at the floor. The budget floor, in turn, is the minimum of past budgets and the spending required to complete all work. Thus, the budget cannot be reduced until proactive work no longer remains.

Maintenance Spending

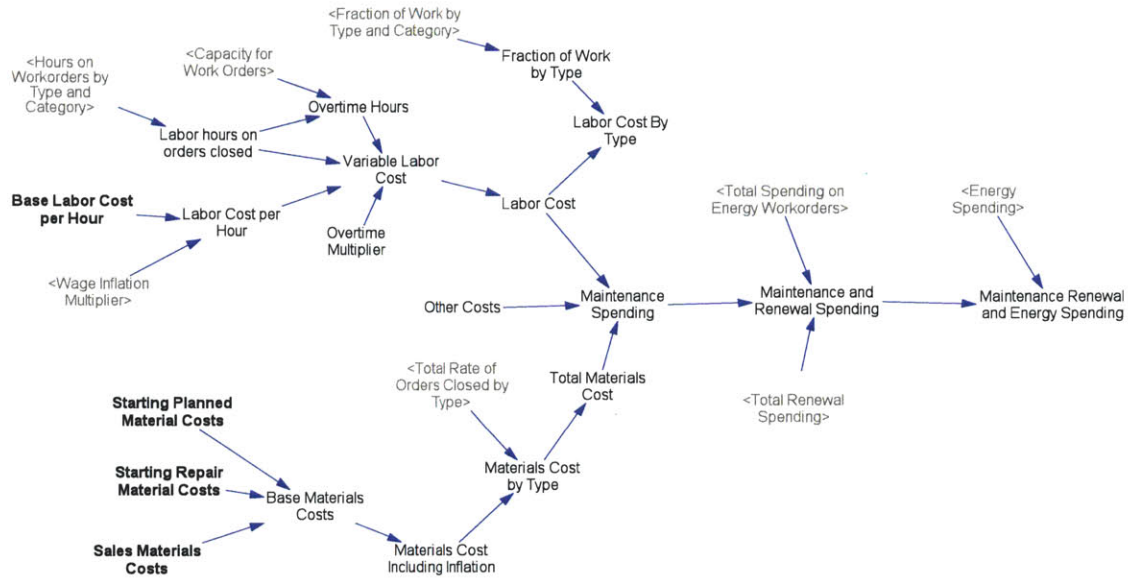


Figure 13: Model Diagram for Maintenance Spending

Spending is shown in Figure 13. Maintenance spending has three components: labor spending, materials spending, and fixed costs. Labor spending is calculated as total hours worked times the hourly wage, with time and a half for overtime. Materials spending is the rate of work orders closed multiplied by the cost per work order. The entire model is run in real (2005) dollars, so materials costs remain constant. (The rate of inflation is set to zero).

Model runs also show renewal spending and energy spending. Renewal spending is an exogenous parameter. Energy spending is determined by the “energy requirements of buildings” described above. Spending equals energy requirements (mbtu/year) multiplied by the price (\$/mbtu) for each of the three types of energy consumption. In the base run, we assume that energy prices are constant. Sensitivity runs for different energy price trajectories are not shown here but can be easily created.

Calculating the NPV of Investment

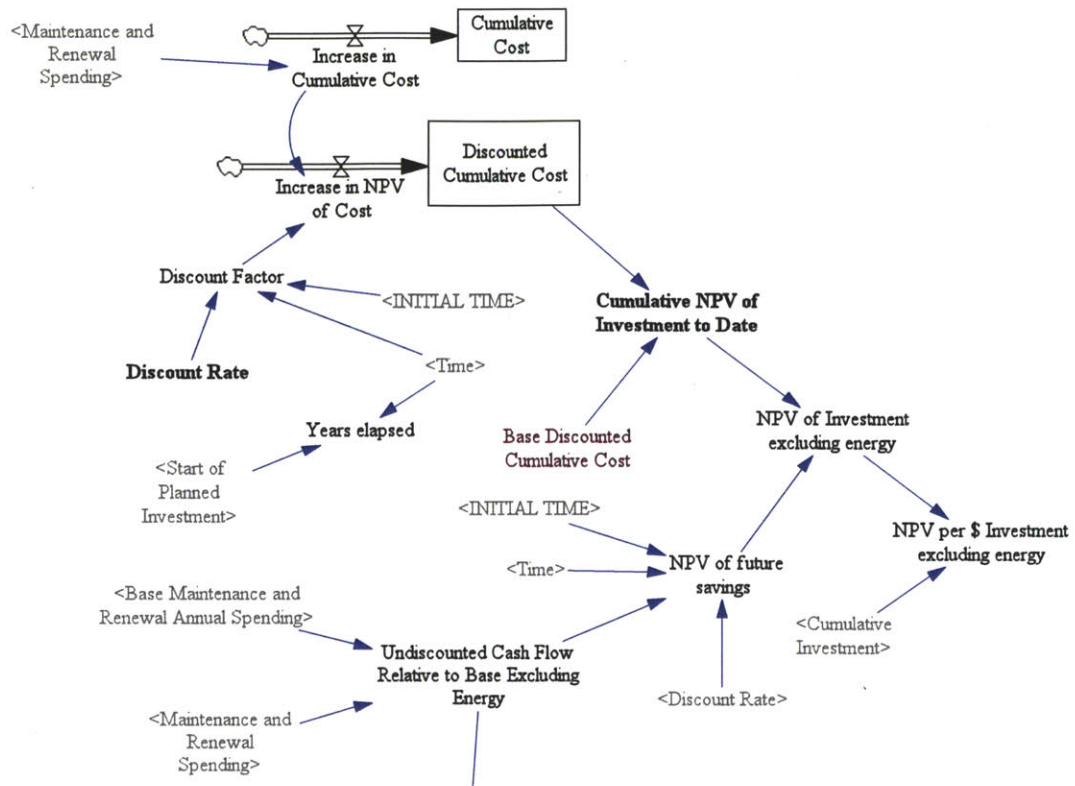


Figure 14: Model Diagram for the NPV Calculation

The final sector of the model is the financial sector. The financial sector calculates the NPV of each policy run relative to a base run.

The NPV of a policy has two components: the difference in discounted cumulative spending through the end of the simulation (in 2025), and an estimate of the NPV of future savings past the end of the simulation. Given an interest rate of 5%, savings past 2025 still have substantial positive present value.

For each run, we accumulate discounted spending in a stock of “cumulative discounted spending.” At any point in time, discounted spending is spending multiplied by a discount factor. The discount factor is e^{-rt} , where r is the interest rate and t is the time. We store cumulative discounted spending for a base run, and compare against each policy run. To calculate future savings, we assume that the difference between base spending and policy spending at the end of the simulation remains constant and apply a formula for total NPV from 2025 on. (Similar to equation 5 above).

The variable NPV per \$ investment is the final NPV divided by the initial proactive investment.

The same procedure is followed for spending that includes energy savings.

Complete Listing of Model Equations

"\$ per Million \$"=

1e+006

Units: \$/Million\$

Additional Budget from Policies=

Additional Policy Spending on Planned Work*Switch for Policy Spending through Budget
+Energy Savings to Reinvest

Units: \$/Year

Additional Defect Creation from Item[Item]=

Defect Creation Rate by Item[Item]-Defect Creation Rate by Item if Good Condition

[Item]

Units: Defects/Year

Additional Defect Creation Rate by Category and Item[AB,Item]=

IF THEN ELSE(Category by Item[Item]=1,Additional Defect Creation from Item[Item

],0)

Additional Defect Creation Rate by Category and Item[C,Item]=

IF THEN ELSE(Category by Item[Item]=2,Additional Defect Creation from Item[Item

],0)

Additional Defect Creation Rate by Category and Item[D2,Item]=

IF THEN ELSE(Category by Item[Item]=3,Additional Defect Creation from Item[Item

],0)

Additional Defect Creation Rate by Category and Item[D3,Item]=

IF THEN ELSE(Category by Item[Item]=4,Additional Defect Creation from Item[Item

],0)

Additional Defect Creation Rate by Category and Item[D45,Item]=

IF THEN ELSE(Category by Item[Item]=5,Additional Defect Creation from Item[Item

],0)

Additional Defect Creation Rate by Category and Item[Other,Item]=

IF THEN ELSE(Category by Item[Item]=6,Additional Defect Creation from Item[Item

],0)

Units: Defects/Year

Additional External Spending Amount=

0

Units: Million\$/Year

Additional Policy Spending on Planned Work=

IF THEN ELSE(Time>Start of Planned Investment, IF THEN ELSE(Time<End of Planned
Investment

,Planned Spending Pulse Height*"\$ per Million \$",0),0)

Units: \$/Year

Additional Proactive Spending on Renewal=

MAX(0,Renewal Budget-Maintenance Spending on Renewal)

Units: \$/Year

Additional Spending End Time=

2010

Units: Year

Additional Spending Start Time=

2008

Units: Year

Adjustment for Staff=

$((\text{Desired Staff Level}-\text{Labor Force})/\text{Time to Adjust Staff})*\text{Switch for staff adjustment}$

Units: ppl/Year

Adjustment for staff is desired staff minus actual staff divided by an adjustment time, which is assumed to be different for reducing staff than it is for increasing staff. Switch allows staff adjustment to be disabled (so that labor remains constant)

Adjustment to Base Budget from need=

$\text{MIN}(\text{Maximum Budget Increase},\text{Base Budget Gap}/\text{Time to adjust Base budget})$

Units: \$/Year/Year

Aging per year=

1

Units: Year/Year

alpha=

0.006

Units: Year/hours [0,?]

Attractiveness by Type[Type]=

$\exp(\alpha*\text{Total DCR by Type}[\text{Type}]/365)$

Units: dmnl

The logit model is used to allocate work among priorities

Attrition=

$\text{Labor Force}*\text{Fractional Attrition Rate}$

Units: ppl/Year

The number of people leaving per month

Average Annual ROI Excluding Energy=

$\text{zidz}(\text{Fractional Return},\text{Years elapsed})$

Units: 1/Year

Average Annual ROI including Energy=

$\text{zidz}(\text{Fractional Return including energy},\text{Years elapsed})$

Units: 1/Year

Average Cost per WO=

$\text{zidz}(\text{SUM}(\text{Average Cost per WO by Type}[\text{Type!}]*\text{Total Rate of Orders Closed by Type}[\text{Type!}]),\text{SUM}(\text{Total Rate of Orders Closed by Type}[\text{Type!}]))$

Units: \$/workorder

Average Cost per WO by Category[Category]=

$\text{zidz}(\text{SUM}(\text{Rate of Orders Closed}[\text{Type!},\text{Category}]*\text{Current Cost per WO by type and category}[\text{Type!},\text{Category}]),\text{Total Rate of Orders Closed by Category}[\text{Category}])$

Units: \$/workorder

Average Cost per WO by Type[Type]=

$\text{zidz}(\text{SUM}(\text{Rate of Orders Closed}[\text{Type},\text{Category!}]*\text{Current Cost per WO by type and category}[\text{Type},\text{Category!}]),\text{Total Rate of Orders Closed by Type}[\text{Type}])$

Units: \$/workorder

Average Delivery Delay[Type]=
zidz(SUM(Backlog[Type,Category!]),SUM(Rate of Orders Closed[Type,Category!]))
Units: Year

Average Hours Charged per Hour Worked=
1
Units: hours/hours

Average Hours per week per person=
35.19
Units: hours/week/people

Average Lifetime as Defect[Category]= INITIAL(
zidz(Defects[Category],Total defect Elimination[Category]))
Units: years

Average Time to Complete Repair Work=
Average Time to Complete Work Orders[Repair]
Units: weeks

Average Time to Complete Work Orders[Type]=
zidz(SUM(Backlog[Type,Category!]),SUM(Rate of Orders Closed[Type,Category!]))*weeks per
year
Units: weeks

Backlog[Type,Category]= INTEG (
Rate of New Work Orders[Type,Category]-Rate of Orders Closed[Type,Category],
Calculated Initial Backlog[Type,Category])
Units: workorders
The backlog of workorders.

Base Budget Gap=
(Desired Base Budget-Base Internal Budget)
Units: \$/Year

Base Cost per WO by Category[Type,Category]=
zidz(Base Labor Cost per Hour,Base Productivity[Type,Category])+Base Materials Costs
[Type]
Units: \$/workorder

Base Cost per WO by Category and Item[AB,Item]=
IF THEN ELSE(Category by Item[Item]=1,Base Cost per WO by Category[Repair,AB],0
)

Base Cost per WO by Category and Item[C,Item]=
IF THEN ELSE(Category by Item[Item]=2,Base Cost per WO by Category[Repair,C],0
)

Base Cost per WO by Category and Item[D2,Item]=
IF THEN ELSE(Category by Item[Item]=3,Base Cost per WO by Category[Repair,D2],
0)

Base Cost per WO by Category and Item[D3,Item]=
IF THEN ELSE(Category by Item[Item]=4,Base Cost per WO by Category[Repair,D3],
0)

Base Cost per WO by Category and Item[D45,Item]=
IF THEN ELSE(Category by Item[Item]=5,Base Cost per WO by Category[Repair,D45]
,0)

Base Cost per WO by Category and Item[Other,Item]=

IF THEN ELSE(Category by Item[Item]=6,Base Cost per WO by Category[Repair,Other],0)
Units: \$/workorder

Base Cost per WO by Item[Item]=
SUM(Base Cost per WO by Category and Item[Category!,Item])
Units: \$/workorder

Base Defect Creation Rate by Item GC[Item]=
Base Defect Creation Rate by Item NR[Item]*Ratio of GC to NR Defect Creation Rate
Units: Defects/Year/\$

Base Defect Creation Rate by Item NR[Item]=
IF THEN ELSE(Category by Item[Item]=1,Base Defect Creation Rate NR by Category[AB],IF THEN ELSE(Category by Item[Item]=2,Base Defect Creation Rate NR by Category[C],IF THEN ELSE(Category by Item[Item]=3,Base Defect Creation Rate NR by Category[D2],IF THEN ELSE(Category by Item[Item]=4,Base Defect Creation Rate NR by Category[D3],IF THEN ELSE(Category by Item[Item]=5,Base Defect Creation Rate NR by Category[D45],IF THEN ELSE(Category by Item[Item]=6,Base Defect Creation Rate NR by Category[Other],0))))))
Units: Defects/Year/\$

Base Defect Creation Rate GC by Category[Category]=
Base Defect Creation Rate NR by Category[Category]*Ratio of GC to NR Defect Creation Rate
Units: Defects/Year/\$

Base Defect Creation Rate NR by Category[Category]=
Base Rate of Defect Creation[Category]/(Ratio of GC to NR Defect Creation Rate*
Initial GC Stock by Category
[Category]+Initial NR Stock by Category[Category])
Units: Defects/Year/\$

Base Desired Time to Complete Work Orders[Type]=
0.08,0.08,0.16
Units: Year
0.042,0.042,0.083

Results of optimization - 6,11.6,12.7,12.6,18.1,35 (However, this gives Work pressure that is too low, so adjust 10,20, and 30 down to be closer to stated goals and raise WP)

Base Discounted Cumulative Cost:INTERPOLATE::=
GET XLS DATA('data for vensim.xls', 'FinancialBase', 'A', 'B2')
Units: \$

Base Discounted Total Cost:=
GET XLS DATA('data for vensim.xls', 'FinancialBase', 'A', 'D2')
Units: \$

Base Energy Spending:=
GET XLS DATA('data for vensim.xls', 'FinancialBase', 'A', 'E2')
Units: \$/Year

base energy weight=
0
Units: dmn1

Base Hazard Rate[Category]= INITIAL(
zidz(Initial Repair WO Rate[Category],Initial Defects[Category]))
Units: workorders/Year/Defect

Base Initial Years of Accumulated Defects[Category]=
15,15,7,7,15,7
Units: years

Base Internal Budget= INTEG (
Adjustment to Base Budget from need+Increase in Internal Budget,
Initial Internal Budget)
Units: \$/Year

Base Labor Cost per Hour=
30
Units: \$/hour

Base Maintenance and Renewal Annual Spending:INTERPOLATE::=
GET XLS DATA('data for vensim.xls', 'FinancialBase', 'A', 'C2')
Units: \$/Year

Base Mandated PM=
14348.3
Units: hours/Year

Base Materials Costs[Repair]=
Starting Repair Material Costs
Base Materials Costs[Sales]=
Sales Materials Costs
Base Materials Costs[Planned]=
Starting Planned Material Costs
Units: \$/workorder

Base Minimum Required on Maintenance Renewal and Energy=
Base Energy Spending+Base Minimum Required Spending on Maintenance and Renewal
Units: \$/Year

Base Minimum Required Spending on Maintenance and Renewal:=
GET XLS DATA('data for vensim.xls', 'FinancialBase', 'A', 'G2')
Units: \$/Year

Base Planned Hours on Renewals=
Fraction of Planned Work for Renewals*Potential Planned Hours
Units: hours/Year

Base Productivity[Type,Category]=
Reference Productivity[Type,Category]/Initial Productivity Multiplier
Units: workorders/hour

Base Rate of Defect Creation[Category]=
zidz(Equilibrium Base Rate of Defect Creation[Category],Initial Effects on NDC[
Category])-Initial Defect Creation from Collateral Damage[Category]
Units: Defects/Year

Base Rate of External Planned Spending=

40

Units: Million\$/Year

Base Renewal Costs[Item]=

GET XLS CONSTANTS('Data for vensim.xls' , 'Renewals' , 'L2*')

Units: \$

Base Spending Including Utilities:=

GET XLS DATA('data for vensim.xls', 'FinancialBase', 'A', 'F2')

Units: \$/Year

Base spending per WO by type[Type]=

INITIAL(Spending per WO by Type[Type])

Units: \$/workorder

Base Utilities Spending:=

GET XLS DATA('data for vensim.xls', 'FinancialBase', 'A', 'E2')

Units: \$/Year

Base Year for Inflation=

2007

Units: Year

Breakdowns per GSF=

Total Workorder Creation Rate/Gross Square Feet Maintained

Units: workorders/Year/GSF

Calculated Initial Backlog[Type,Category]=

(Desired Time to Complete Work Orders[Type]*Initial Desired Completion Rate[Type
,Category]*Base Productivity[Type,Category
)*(1-Switch for proportional allocation)+Switch for proportional allocation*Calculated Initial

Backlog with Proportional Allocation

[Type,Category]

Units: workorders

Calculated Initial Backlog with Proportional Allocation[Type,Category]=

Desired Time to Complete Work Orders[Type]*Initial DCR with Proportional Allocation
[Type,Category]*Base Productivity[Type,Category]

Units: workorders

Calculated simple payback time by item[Item]=

xidz(Renewal Cost by Item[Item],Total potential dollar savings by item[Item],100000

)

Units: years

Capacity for Work Orders=

Work Capacity-Surplus Hours+Policy Capacity Available

Units: hours/Year

Category:

AB,C,D2,D3,D45,Other

Category by Item[Item]=

GET XLS CONSTANTS('Data for vensim.xls' , 'Renewals' , 'M2*')

Units: dmnl

Category2:
Cat1,Cat2,Cat3,Cat4,Cat5,Cat6

Change in GSF=
IF THEN ELSE(Time<Time for Endogenous Growth,GSF Data(Time),Gross Square Feet
Maintained
*Endogenous Rate of GSF Growth)
Units: square feet/Year

Change in Inflation Multiplier=
Materials Inflation Multiplier*Materials Rate of Inflation
Units: 1/Year

Change in Wage multiplier=
Wage Rate of Inflation*Wage Inflation Multiplier
Units: 1/Year

Contribution to Bldg System Energy Requirements by energy type[Category,EnergyType
]=TABBED ARRAY(
0.25 0 0.25
0 0 0
0 0 0
0.75 0.5 0.75
0 0.5 0
0 0 0
)
Units: dmnl

Conversion factor for renewal spending=
1/((1+Rate of inflation for renewal costs)^Years to calculate inflation)
Units: dmnl

Cost of Mandatory Work at Expected Productivity=
SUM(Expected Cost of Mandatory Planned Work[Category!])+SUM(Current Cost of Workorders
at Expected Productivity
[Repair,Category
!])
+SUM(Current Cost of Workorders at Expected Productivity[Sales,Category!])+Other Costs
Units: \$/Year

Cost of workorders generated by item[Item]= INITIAL(
RANDOM NORMAL(0, 1000 , Base Cost per WO by Item[Item], Workorder Cost Std Deviation
[Item] , 1))
Units: \$/workorder

Cost per Work Order at Reference Productivity[Type,Category]=
zidz(Normal Labor cost per hour including overtime,Reference Productivity[Type,
Category])+Materials Cost Including Inflation[Type]
Units: \$/workorder

Cumulative Cost= INTEG (
Increase in Cumulative Cost,
0)
Units: \$

Cumulative Cost Including Utilities= INTEG (

Increase in Cumulative Total Cost,
0)
Units: \$

Cumulative Investment= INTEG (
Increase in Cumulative Investment,
0)
Units: \$

Cumulative Net Dollar Return= INTEG (
Increase in net Cumulative Return,
0)
Units: \$

Cumulative Net Dollar Return on Investment including energy= INTEG (
Increase in net Cumulative Return including energy,
0)
Units: \$

Cumulative NPV including Energy Savings=
Base Discounted Total Cost-Discounted Total Cumulative Cost
Units: \$

Cumulative NPV of Investment to Date=
Base Discounted Cumulative Cost-Discounted Cumulative Cost
Units: \$

Cumulative Return from Reduced Energy Use= INTEG (
Increase in Return from reduced energy use,
0)
Units: \$

Cumulative Return from Reduced Energy Use with interest earned= INTEG (
Increase in Return from reduced energy use+Interest earned on return from energy
,
0)
Units: \$

Current Budget Pressure=
zidz(Current Cost of Mandatory Work with Base Planned,Internal Budget)
Units: dml

Current Cost for Repair and Sales=
SUM(Current Cost of Workorders by Type and Category[Repair,Category!])+SUM(Current Cost
of Workorders by Type and Category
[Sales,Category
!])
Units: \$/Year

Current Cost of Mandatory Planned Work 0[Category]=
Current Mandatory Planned Workorders 0[Category]*Current Cost per WO by type and category
[Planned,Category]
Units: \$/Year

Current Cost of Mandatory Planned Work 0 0[Category]=

Current Mandatory Planned Workorders 0 0 0[Category]*Cost per Work Order at Reference
Productivity
[Planned,Category]
Units: \$/Year

Current Cost of Mandatory Planned Work 0 0 0[Category]=
Current Mandatory Planned Workorders 0 0 0[Category]*Expected Cost per WO by type and
Category
[Planned,Category]
Units: \$/Year

Current Cost of Mandatory Work with Base Planned=
SUM(Current Cost of Mandatory Planned Work 0[Category!])+SUM(Current Cost of Workorders
by Type and Category
[Repair,Category
!])
+SUM(Current Cost of Workorders by Type and Category[Sales,Category!])+Other Costs
Units: \$/Year

Current Cost of Mandatory Work with Base Planned at Expected Productivity=
SUM(Current Cost of Mandatory Planned Work 0 0 0[Category!])+SUM(Current Cost of
Workorders at Expected Productivity
[Repair
,Category
!])
+SUM(Current Cost of Workorders at Expected Productivity[Sales,Category!])+Other Costs
Units: \$/Year

Current Cost of Mandatory Work with Base Planned at Reference Productivity=
SUM(Current Cost of Mandatory Planned Work 0 0[Category!])+SUM(Current Cost of
Workorders at Reference Productivity
[Repair
,Category
!])
+SUM(Current Cost of Workorders at Reference Productivity[Sales,Category!])+Other Costs
Units: \$/Year

Current Cost of Workorders at Expected Productivity[Type,Category]=
Desired Completion Rate by Type and Category[Type,Category]*Expected Cost per WO by type
and Category
[Type,Category]
Units: \$/Year

Current Cost of Workorders at Reference Productivity[Type,Category]=
Cost per Work Order at Reference Productivity[Type,Category]*Desired Completion Rate by
Type and Category
[Type,Category]
Units: \$/Year

Current Cost of Workorders by Type and Category[Type,Category]=
Current Cost per WO by type and category[Type,Category]*Desired Completion Rate by Type
and Category
[Type,Category]
Units: \$/Year

Current Cost per WO by type and category[Type,Category]=

zidz(Normal Labor cost per hour including overtime,Productivity[Type,Category])
+Materials Cost Including Inflation[Type]
Units: \$/workorder

Current Energy Requirements by Bldg System[Category]=
Total Energy Requirements by Category[Category]/GSF for Categories
Units: mBTU/Year/GSF

Current Mandatory Planned Hours by Category[Category]=
Mandated Planned Hours*Fraction of Work by Type and Category[Planned,Category]
Units: hours/Year

Current Mandatory Planned Hours by Category 0[Category]=
Base Mandated PM*Fraction of Work by Type and Category[Planned,Category]
Units: hours/Year

Current Mandatory Planned Workorders 0[Category]=
Current Mandatory Planned Hours by Category 0[Category]*Productivity[Planned,Category]
]
Units: workorders/Year

Current Mandatory Planned Workorders 0 0[Category]=
Current Mandatory Planned Hours by Category 0[Category]*Reference Productivity[
Planned,Category]
Units: workorders/Year

Current Mandatory Planned Workorders 0 0 0[Category]=
Current Mandatory Planned Hours by Category 0[Category]*Expected Productivity for planning
[Planned,Category]
Units: workorders/Year

Current Maximum Spending=
Current Cost for Repair and Sales+Current total maximum spending on planned work
+Other Costs
Units: \$/Year

Current Price of Energy=
22
Units: \$/mBTU

Current Rate of Investment=
MAX(0,Maintenance and Renewal Spending-Minimum Required Spending on Maintenance and
Renewal
)
Units: \$/Year

Current Return=
MAX(0,Base Minimum Required Spending on Maintenance and Renewal-Minimum Required
Spending on Maintenance and Renewal
)
Units: \$/Year

Current Spending On Renewals[Item]= INTEG (
Increase in Current Spending on Renewals[Item]-Project Completion[Item],
0)
Units: \$

Current total maximum spending on planned work=
SUM(Maximum spending on planned work by category[Category!])
Units: \$/Year

DCR Std Dev factor=
0.3
Units: dmnl

Defect Creation from Collateral Damage[Category,Category2]=
Workorder Creation Rate[Category]*New DCR rate from breakdowns[Category,Category2]
]*Switch for Collateral Damage
Units: Defect/Year

Defect Creation Rate by Category[AB]=
SUM(Defect Creation Rate by Category and Item[AB,Item!])
Defect Creation Rate by Category[C]=
SUM(Defect Creation Rate by Category and Item[C,Item!])
Defect Creation Rate by Category[D2]=
SUM(Defect Creation Rate by Category and Item[D2,Item!])
Defect Creation Rate by Category[D3]=
SUM(Defect Creation Rate by Category and Item[D3,Item!])
Defect Creation Rate by Category[D45]=
SUM(Defect Creation Rate by Category and Item[D45,Item!])
Defect Creation Rate by Category[Other]=
SUM(Defect Creation Rate by Category and Item[Other,Item!])
Units: Defects/Year

Defect Creation Rate by Category and Item[AB,Item]=
IF THEN ELSE(Category by Item[Item]=1,Defect Creation Rate by Item[Item],0)
Defect Creation Rate by Category and Item[C,Item]=
IF THEN ELSE(Category by Item[Item]=2,Defect Creation Rate by Item[Item],0)
Defect Creation Rate by Category and Item[D2,Item]=
IF THEN ELSE(Category by Item[Item]=3,Defect Creation Rate by Item[Item],0)
Defect Creation Rate by Category and Item[D3,Item]=
IF THEN ELSE(Category by Item[Item]=4,Defect Creation Rate by Item[Item],0)
Defect Creation Rate by Category and Item[D45,Item]=
IF THEN ELSE(Category by Item[Item]=5,Defect Creation Rate by Item[Item],0)
Defect Creation Rate by Category and Item[Other,Item]=
IF THEN ELSE(Category by Item[Item]=6,Defect Creation Rate by Item[Item],0)
Units: Defects/Year

Defect Creation Rate by Item[Item]=
Defect Creation Rate Good Condition[Item]*Good Condition Renewal Costs by Item[
Item]+Defect Creation Rate Needs Renewal
[Item]*Needs Renewal Inventory by Item[Item]
Units: Defects/Year

Defect Creation Rate by Item if Good Condition[Item]=
Renewal Cost by Item[Item]*Defect Creation Rate Good Condition[Item]
Units: Defects/Year

Defect Creation Rate Good Condition[Item]= INITIAL(
RANDOM NORMAL(0,100 , Base Defect Creation Rate by Item GC[Item], GC Defect Creation
Rate Std Dev
[Item], 1))

Units: Defects/Year/\$

Defect Creation Rate Needs Renewal[Item]= INITIAL(
RANDOM NORMAL(0, 100, Base Defect Creation Rate by Item NR[Item], NR DCR Std Dev
[Item], 1))

Units: Defects/Year/\$

Defect Elimination through Planned Maintenance[Category]=
MIN(Defects Eliminated through Planned Workorders[Category],Maximum Rate of Defect
Elimination
[Category
]-Defect Elimination Through Repair[Category]
) *Switch for Defect Elimination

Units: Defects/Year

Defect Elimination Through Repair[Category]=
MIN(Defects Eliminated through Repair[Category],Maximum Rate of Defect Elimination
[Category]) *Switch for Defect Elimination

Units: Defects/Year

Defect Growth Factor=

1

Units: dnm1 [0,3,0.1]

Defects[Category]= INTEG (
Rate of New Defect Creation[Category]-Defect Elimination through Planned Maintenance
[Category]-Defect Elimination Through Repair[Category],
Initial Defects[Category])

Units: Defects

Defects Eliminated per Planned Workorder=

Reference Defects per WO[Planned]*Effect of Work Quality on Defects Eliminated per WO
[Planned]

Units: Defects/workorder

Defects Eliminated through Planned Workorders[Category]=

Rate of Orders Closed[Planned,Category]*Defects Eliminated per Planned Workorder

Units: Defects/Year

Defects Eliminated through Repair[Category]=

Rate of Orders Closed[Repair,Category]*Defects Resolved per Repair Workorder

Units: Defects/Year

Defects Resolved per Repair Workorder=

Reference Defects per WO[Repair]*Effect of Work Quality on Defects Eliminated per WO
[Repair]

Units: Defects/workorder

Deferred Maintenance Backlog=

Total Defects*Base spending per WO by type[Planned]/Reference Defects per WO[Planned
]+Total Renewal Backlog

Units: \$

Desired Additional External Spending=

(STEP(Additional External Spending Amount, Additional Spending Start Time)-STEP
(Additional External Spending Amount,Additional Spending End Time

))*Switch for Additional External Spending
Units: Million\$/Year

Desired Base Budget=
MAX(Current Cost of Mandatory Work with Base Planned at Expected Productivity,Minimum
Desired budget
)
Units: \$/Year

Desired Completion Rate by Type and Category[Type,Category]=
Backlog[Type,Category]/Desired Time to Complete Work Orders[Type]
Units: workorders/Year
The Desired Completion rate, indexed by priority. The desired
completion rate reflects both expected incoming orders and a
correction for current backlog.

Desired Completion Rate in hours[Type,Category]=
zidz(Desired Completion Rate by Type and Category[Type,Category],Base Productivity
[Type,Category])
Units: hours/Year

Desired Completion Rate in Hours at Current Productivity[Type, Category]=
zidz(Desired Completion Rate by Type and Category[Type,Category],Productivity[Type
,Category])
Units: hours/Year

Desired Completion Rate in Hours at Expected Productivity[Type, Category]=
zidz(Desired Completion Rate by Type and Category[Type,Category],Expected Productivity for
hiring and planning
[Type,Category])
Units: hours/Year

Desired External Spending=
(Base Rate of External Planned Spending+Desired Additional External Spending)*"\$ per Million
\$"
Units: \$/Year

Desired Investment=
0
Units: **undefined**

Desired overtime hours per person for planning=
Initial overtime hours per person
Units: hours/week/person

Desired Renewal Spending by Category[Category]=
SUM(Desired Renewal Spending by Category and Item[Category,Item!])
Units: \$/Year

Desired Renewal Spending by Category and Item[AB,Item]=
IF THEN ELSE(Category by Item[Item]=1,Desired Renewal Spending by Item[Item],0)
Desired Renewal Spending by Category and Item[C,Item]=
IF THEN ELSE(Category by Item[Item]=2,Desired Renewal Spending by Item[Item],0
)
Desired Renewal Spending by Category and Item[D2,Item]=
IF THEN ELSE(Category by Item[Item]=3,Desired Renewal Spending by Item[Item],0

)
 Desired Renewal Spending by Category and Item[D3,Item]=
 IF THEN ELSE(Category by Item[Item]=4,Desired Renewal Spending by Item[Item],0
)
 Desired Renewal Spending by Category and Item[D45,Item]=
 IF THEN ELSE(Category by Item[Item]=5,Desired Renewal Spending by Item[Item],0
)
 Desired Renewal Spending by Category and Item[Other,Item]=
 IF THEN ELSE(Category by Item[Item]=6,Desired Renewal Spending by Item[Item],0
)
 Units: \$/Year

Desired Renewal Spending by Item[Item]=
 MIN(Needs Renewal Inventory by Item[Item]/Minimum Time to complete Renewal,(Needs
 Renewal Inventory by Item
 [Item]-Current Spending On Renewals[Item])/TIME STEP)
 Units: \$/Year

Desired Renewal Spending once NR[Item]=
 Renewal Cost by Item[Item]/Minimum Time to complete Renewal
 Units: \$/Year

Desired Staff Level=
 MIN(Potential Staff Level at Current Budget and Allocation,Maximum Desired Staff on Defects
)
 Units: ppl
 MAX(Mandatory Desired Staff+MIN(Potential Additional Staff from Budget
 Surplus,Maximum desired staff on planned work above mandatory
),Staff Minimum)

Desired Time to complete repair work=
 Desired Time to Complete Work Orders[Repair]*weeks per year
 Units: weeks

Desired Time to Complete Work Orders[Type]=
 smoothi(Base Desired Time to Complete Work Orders[Type]*Effect of Work Pressure on Desired
 Completion Time
 ,Time to Adjust DCT,Base Desired Time to Complete Work Orders[Type])*Switch for Endogenous DCT
 +(1-Switch for Endogenous DCT)*Base Desired Time to Complete Work Orders[Type]
 Units: Year
 0.042,0.042,0.083

Results of optimization - 6,11.6,12.7,12.6,18.1,35 (However, this
 gives Work pressure that is too low, so adjust 10,20, and 30 down to
 be closer to stated goals and raise WP)

Discount Factor=
 exp(-Discount Rate*(Time-INITIAL TIME))
 Units: dmn1

Discount Rate=
 0.05
 Units: 1/Year

From John Reed 5/09

Discounted Cumulative Cost= INTEG (

Increase in NPV of Cost,
0)

Units: \$

Discounted Total Cumulative Cost= INTEG (
Increase in NPV of Total Cost,
0)

Units: \$

Effect of Budget Pressure on Quality of Parts=
(Table for effect of budget pressure on quality of parts(Maintenance Budget Pressure
)-1)*Strength of Effects on Defect Creation+1
Units: dmn1

Effect of Campus Condition on Reported Workorders per Year=
Table for Effect of Perceived Campus Condition on Reporting(Perceived Campus Condition
Indicator
)
Units: dmn1

Effect of Campus Size on Defect Creation=
GSF Relative to Initial*Switch for Growing Campus+1-Switch for Growing Campus
Units: dmn1

Effect of Intensity of Use on Defect Creation[Category]=
(Table for Effect of Intensity of Use on Defect Creation(Intensity of Use[Category
)-1)*Sensitivity to Intensity by Category
[Category]*Strength of Effects on Defect Creation+1
Units: dmn1

Effect of Parts Quality on New Defect Creation=
1/Quality of Parts
Units: dmn1

Effect of Service Expectations on Workorders per Defect=
Table for Effect of Service on Opened WO per Defect(Relative Service Quality)
Units: dmn1

Effect of Work Pressure on Desired Completion Time=
Table for Effect of Work Pressure on DCT(Work Pressure)
Units: dmn1

Effect of Work Pressure on Hours Charged=
Table for Effect of Hours Charged(Work Pressure)
Units: dmn1

As work pressure goes up, more hours are charged. This result is not
significant for the most recent formulation of work pressure, for the
entire R&M operation (10/18)

Effect of Work Pressure on Productivity=
Table for Effect of Productivity(Work Pressure)
Units: dmn1

Effect of Work Pressure On Quality of Parts=
(Table for Effect of Work Pressure on Quality of Parts(Work Pressure)-1)*Strength of Effects on
Defect Creation

+1

Units: dmn1

Effect of Work Quality on Defects Eliminated per WO[Type]=

Table for Effect of Work Quality on Defects Elim per WO(Work Quality[Type])

Units: dmn1

Effect of Work Quality on New Defect Creation=

(Table for Effect of Work Quality on New Defect Creation(Work Quality[Repair])-

1)*Strength of Effects on Defect Creation+1

Units: dmn1

Effective Renewal spending on Repair[Category]=

Renewal Cost from Repair[Category]/(1+Renewal Markup when Reactive)

Units: \$/Year

Effects on New Defect Creation[Category]=

Effect of Intensity of Use on Defect Creation[Category]*Effect of Parts Quality on New Defect
Creation

*Effect of Work Quality on New Defect Creation*Switch for Effects on New Defect Creation
+(1-Switch for Effects on New Defect Creation)

Units: dmn1

End of Planned Investment=

2009

Units: Year [2006,2013]

Endogenous Opened WOs[Repair,Category]=

Repair Opened Workorders[Category]

Endogenous Opened WOs[Planned,Category]=

Planned Opened Workorders[Category]

Endogenous Opened WOs[Sales,Category]=

Sales Opened Workorders by Category[Category]

Units: workorders/Year

Endogenous Rate of GSF Growth=

0.01

Units: 1/Year

Energy Cost by Type[EnergyType]=

Energy Requirements by EnergyType[EnergyType]*Price of Energy by Type[EnergyType

]

Units: \$/Year

Energy Price by Year[EnergyType]:=

GET XLS DATA('Data for vensim.xls', 'EnergyPrices', 'A', 'E2')

Units: \$/mBTU

Energy Requirements by Category and EnergyType[Category,EnergyType]= INTEG (

Increase in Energy Requirements by Item[Category,EnergyType]-Reduction in Energy
Requirements by Category and type

[Category,EnergyType],

Initial Energy Requirements by Item[Category,EnergyType])

Units: mBTU/Year

Energy Requirements by EnergyType[EnergyType]=

SUM(Energy Requirements by Category and EnergyType[Category!,EnergyType])
Units: mBTU/Year

Energy Requirements per gsf[EnergyType]=
Energy Requirements by EnergyType[EnergyType]/GSF by Energy Type[EnergyType]
Units: mBTU/Year/GSF

Energy Savings Available through routine maintenance[Category]=
MAX(0,Total Energy Requirements by Category[Category]-Min Energy Requirements after
Routine Maintenance
[Category])*Switch for Energy Savings from Routine Maintenance
Units: mBTU/Year

Energy Savings from Routine Maintenance[Category]=
Energy Savings per Defect[Category]*Total defect Elimination[Category]
Units: mBTU/Year/Year

Energy Savings per Defect[Category]=
zidz(Energy Savings Available through routine maintenance[Category],Defects[Category
)
Units: mBTU/Year/Defect

Energy Savings to Reinvest=
smooth(Total current dollar value of energy savings*Fraction of Energy Savings to Reinvest
*Switch for Energy Reinvestment,Time to reinvest energy savings
)
Units: \$/Year

Energy Spending=
Total Energy Cost
Units: \$/Year

Energy Weight Step=
0
Units: dnm1

Energy Weight Step time=
2008
Units: Year

EnergyType:
CW,Electricity,Steam

Equilibrium Base Rate of Defect Creation[Category]= INITIAL(
Reference Productivity[Repair,Category]*Initial Hours Worked on Work Orders*Initial Fraction
of Hours by Type and Category
[Repair,Category]*Initial Defects Elim per WO[Repair]+Reference Productivity[Planned
,Category]*Initial Hours Worked on Work Orders*Initial Fraction of Hours by Type and Category
[Planned,Category]*Initial Defects Elim per WO[Planned])
Units: Defects/Year

Exogenous Rate of Sales Workorders(
[(2005,0)-(2020,20000)],(2005,8920),(2006.01,9122.81),(2006.93,10000),(2008.03,
10175.4),(2019.95,11491.2))
Units: workorders/Year

Exogenous Starting backlog[Repair]= INITIAL(
 Exogenous starting Repair backlog)
 Exogenous Starting backlog[Planned]= INITIAL(
 Exogenous Starting PM Backlog)
 Exogenous Starting backlog[Sales]= INITIAL(
 Exogenous Starting Sales Backlog)
 Units: workorders

Exogenous Starting PM Backlog=
 850
 Units: workorders

Exogenous starting Repair backlog=
 2160
 Units: workorders

Exogenous Starting Sales Backlog=
 900
 Units: workorders

Expected Attrition=
 smooth(Attrition,Time to form Attrition Expectations)
 Units: ppl/Year
 Expected attrition, which is a smooth of actual attrition, used for
 the purpose of hiring new staff

Expected Average Cost per WO[Type]=
 SUM(Weighted Cost per WO[Type,Category!])
 Units: \$/workorder

Expected average dollars per hour=
 SUM(Weighted dollars per hour at expected work allocation[Type!,Category!])
 Units: \$/hour

Expected Average Productivity for hiring and planning[Type]=
 SUM(Weighted Expected Productivity[Type,Category!])
 Units: workorders/hour

Expected Average Productivity for opened work[Type]=
 SUM(Weighted Expected Productivity 0[Type,Category!])
 Units: workorders/hour

Expected Budget Surplus or Deficit after Mandatory work=
 Base Internal Budget-Cost of Mandatory Work at Expected Productivity
 Units: \$/Year

Expected Cost of Mandatory Planned Work[Category]=
 Expected Mandatory Planned Workorders[Category]*Expected Cost per WO by type and
 Category
 [Planned,Category]
 Units: \$/Year

Expected Cost per WO by type and Category[Type,Category]=
 zidz(Normal Labor cost per hour including overtime,Expected Productivity for planning
 [Type,Category])+Materials Cost Including Inflation[Type]
 Units: \$/workorder

Expected Fraction of Hours by Type and Category[Type,Category]=
smooth(Fraction of Hours Worked by Type and Category[Type,Category],Time to form
expectations for hiring and planning
)
Units: dmn1

Expected Fraction of Work by Category[Type,Category]=
smooth(zidz(Fraction of Work by Type and Category[Type,Category],SUM(Fraction of Work by
Type and Category
[Type,Category!])),Time to form expectations for hiring and planning)
Units: dmn1

Expected Fraction of Work by Category 0[Type,Category]=
smooth(zidz(Fraction of Work by Type and Category[Type,Category],SUM(Fraction of Work by
Type and Category
[Type,Category
!])),Time to form expectations for hiring and planning)
Units: dmn1

Expected Hours Available for Supplementary Planned Work=
MAX(0,Work Capacity-Expected Mandatory Workload)
Units: hours/Year

Expected Mandatory Planned Workorders[Category]=
Current Mandatory Planned Hours by Category[Category]*Expected Productivity for planning
[Planned,Category]
Units: workorders/Year

Expected Mandatory Workload=
smoothi(SUM(Mandatory Desired Completion Rate in Hours[Type!,Category!]),Time to form
expectations for hiring and planning
,Initial Hours Worked on Work Orders
)
Units: hours/Year

Expected Productivity for hiring and planning[Type,Category]=
smoothi(Productivity[Type,Category],Time to form expectations for hiring and planning
,Reference Productivity[Type,Category]
)
Units: workorders/hour

Expected Productivity for planning[Type,Category]=
smoothi(Productivity[Type,Category],Time to adjust Productivity Expectations,Reference
Productivity
[Type,Category
])
Units: workorders/hour

Expected Surplus for Planned Work=
MAX(0,Expected Budget Surplus or Deficit after Mandatory work+Additional Budget from
Policies
)
Units: \$/Year

FINAL TIME = 2025

Units: Year

The final time for the simulation.

Fraction Good Condition=

Total Good Condition Assets/(Total Good Condition Assets+Total Renewal Backlog)

Units: dmn1

Fraction of DCR by Category[Type,Category]=

zidz(Desired Completion Rate in hours[Type,Category],SUM(Desired Completion Rate in hours [Type,Category!]))

Units: dmn1

Fraction of DCR by Type and Category[Type,Category]=

zidz(Desired Completion Rate in hours[Type,Category],SUM(Desired Completion Rate in hours [Type!,Category!]))

Units: dmn1

Fraction of Defects that require renewal=

0

Units: dmn1

Fraction of Energy Savings to Reinvest=

0

Units: dmn1 [0,1]

Fraction of Hours Proactive=

(Planned Hours Worked+Internal Work Hours unused)/(Internal Work Hours unused+Planned Hours Worked +Repair Hours Worked+Sales Hours Worked)

Units: dmn1

Fraction of Hours Repair=

SUM(Fraction of Work by Type and Category[Repair,Category!])

Units: dmn1

Fraction of Hours Sales=

SUM(Fraction of Work by Type and Category[Sales,Category!])

Units: dmn1

Fraction of Hours Worked by Type and Category[Type,Category]=

Potential hours on Workorders at current budget[Type,Category]/SUM(Potential hours on Workorders at current budget [Type!,Category!])

Units: dmn1

Fraction of Maintenance Savings Achievable through routine maintenance[Category]

=

0.2,0,0,0.5,0.1,0

Units: dmn1

Fraction of orders charged labor[Type]=

1

Units: dmn1

The fraction of orders that require labor. For now, this is exogenous

Fraction of Planned Work for Renewals=

0
Units: dmnl

Fraction of Potential Staff available for renewal=
Potential Additional Staff from Budget Surplus/Potential Staff Level at Current Budget and
Allocation
Units: dmnl

Fraction of Sales WOs by Category[Category]=
Initial Fraction of Hours by Category[Sales,Category]
Units: dmnl

Fraction of WO dollars that resolve defects[Type]=
0.1,0,0.5
Units: dmnl

Fraction of Work by Type[Type]=
SUM(Fraction of Work by Type and Category[Type,Category!])
Units: dmnl

Fraction of Work by Type and Category[Type,Category]=
(Attractiveness by Type[Type]/SUM(Attractiveness by Type[Type!]))*Fraction of DCR by
Category
[Type,Category]*(1-Switch for proportional allocation)+Switch for proportional allocation
*Fraction of DCR by Type and Category[Type,Category]
Units: dmnl

The logit model is used to allocate work among priorities.

Fractional Attrition Rate=
0.1
Units: 1/Year

Fractional Return=
zidz(Cumulative Net Dollar Return,Cumulative Investment)
Units: dmnl

Fractional Return including energy=
zidz(Cumulative Net Dollar Return on Investment including energy,Cumulative Investment
)
Units: dmnl

Full Time Employees=
Labor Force
Units: people [0,600]

GC Defect Creation Rate Std Dev[Item]=
Base Defect Creation Rate by Item GC[Item]*DCR Std Dev factor
Units: Defects/Year/\$

Good Condition[Item]= INTEG (
Rate of New System Creation[Item]+Rate of Renewal[Item]-Reaching End of Life[Item
,
Initial Items in Good Condition[Item])
Units: dmnl

Good Condition Costs by Category and Item[AB,Item]=

IF THEN ELSE(Category by Item[Item]=1,Good Condition Renewal Costs by Item[Item
],0)
Good Condition Costs by Category and Item[C,Item]=
IF THEN ELSE(Category by Item[Item]=2,Good Condition Renewal Costs by Item[Item
],0)
Good Condition Costs by Category and Item[D2,Item]=
IF THEN ELSE(Category by Item[Item]=3,Good Condition Renewal Costs by Item[Item
],0)
Good Condition Costs by Category and Item[D3,Item]=
IF THEN ELSE(Category by Item[Item]=4,Good Condition Renewal Costs by Item[Item
],0)
Good Condition Costs by Category and Item[D45,Item]=
IF THEN ELSE(Category by Item[Item]=5,Good Condition Renewal Costs by Item[Item
],0)
Good Condition Costs by Category and Item[Other,Item]=
IF THEN ELSE(Category by Item[Item]=6,Good Condition Renewal Costs by Item[Item
],0)
Units: \$

Good Condition Discount Factor in Added Energy Costs=
0.2
Units: dmn1

Good Condition Inventory by Category[Category]=
SUM(Good Condition Costs by Category and Item[Category,Item!])
Units: \$

Good Condition Inventory by Item[Item]=
Renewal Cost by Item[Item]*Good Condition[Item]
Units: \$

Good Condition Renewal Costs by Item[Item]=
Good Condition[Item]*Renewal Cost by Item[Item]
Units: \$

Gross Square Feet Maintained= INTEG (
Change in GSF,
Starting GSF)
Units: square feet

GSF by Energy Type[EnergyType]=
6.34224e+006, 1.05615e+007, 8.74583e+006
Units: square feet

GSF Data(
[(2004,-600000)-(2009,600000)],(2004,20000),(2005,420000),(2006,-130000),(2007,
0),(2008,0),(2009,0))
Units: square feet/Year

GSF for Categories=
GSF by Energy Type[Electricity]
Units: GSF

GSF Relative to Initial=
Gross Square Feet Maintained/Starting GSF
Units: dmn1

Hiring=
MAX(0,Adjustment for Staff+Expected Attrition)

Units: ppl/Year

Hiring, measured in people per month. Assumed to be expected attrition plus an adjustment for desired staff

Hours from Policy Spending=
Additional Policy Spending on Planned Work/Expected Average Cost per WO[Planned]/Expected Average Productivity for opened work[Planned]

Units: hours/Year

Hours on Workorders by Type and Category[Type,Category]=
zidz(Rate of Orders Closed[Type,Category],Productivity[Type,Category])

Units: hours/Year

Increase in Cumulative Cost=
Maintenance and Renewal Spending

Units: \$/Year

Increase in Cumulative Investment=
Current Rate of Investment

Units: \$/Year

Increase in Cumulative Total Cost=
Maintenance Renewal and Energy Spending

Units: \$/Year

Increase in Current Spending on Renewals[Item]=
Spending by Item[Item]

Units: \$/Year

Increase in Energy Requirements by Item[Category,EnergyType]=
(MAX(0,Maximum Energy Requirements by Category and Type[Category,EnergyType]-Energy Requirements by Category and EnergyType [Category,EnergyType]))/Time to reach Maximum Energy Requirements[EnergyType]

Units: mBTU/Year/Year

Increase in Internal Budget=
Base Internal Budget*Internal Budget Growth Rate

Units: \$/Year/Year

Increase in Investment Including Energy Savings=
Energy Savings to Reinvest+Additional Policy Spending on Planned Work

Units: \$/Year

Increase in net Cumulative Return=
Current Return

Units: \$/Year

Increase in net Cumulative Return including energy=
MAX(0,Base Minimum Required on Maintenance Renewal and Energy-Minimum Required on Maintenance Renewal and Energy

)
Units: \$/Year

Increase in NPV of Cost=
Discount Factor*Increase in Cumulative Cost
Units: \$/Year

Increase in NPV of Total Cost=
Discount Factor*Increase in Cumulative Total Cost
Units: \$/Year

Increase in Planned Hours Ramp=
0
Units: hours/Year/Year [0,5000,200]
R&M policy runs - increase to 3000

Increase in Policy Investment=
Additional Policy Spending on Planned Work
Units: \$/Year

Increase in Return from reduced energy use=
MAX(0,Base Utilities Spending-Energy Spending)
Units: \$/Year

Increase in Simple Return Excluding Energy=
MAX(0,Undiscounted Cash Flow Relative to Base Excluding Energy)
Units: \$/Year

Increase in Simple Return Including Energy=
MAX(0,Total Undiscounted Cash Flow Relative to Base)
Units: \$/Year

increase in total reductions[EnergyType]=
SUM(Reduction in Energy Requirements by Category and type[Category!,EnergyType]
)
Units: mBTU/Year/Year

Indicated Discretionary PM Allocation[Category]=
Weighted Hours Creation Rate[Category]/SUM(Weighted Hours Creation Rate[Category
!])
Units: dmnl

Indicated Planned Opened Orders by Category[Category]=
MIN(Maximum Hours on Defects by Category[Category],Total Planned Hours on Defects
*Indicated Discretionary PM Allocation
[Category])
Units: hours/Year

Initial Accumulated Defects Factor=
1
Units: dmnl

Initial Attractiveness by Type[Type]=
Initial Attractiveness Multiplier*Initial Fraction of Hours by Type[Type]
Units: dmnl

Initial Attractiveness Multiplier=
(exp(Initial Total Desired Completion Rate*alpha/365))/(Initial Fraction of Hours by Type
[Repair]*Initial Fraction of Hours by Type[Sales]*Initial Fraction of Hours by Type

[Planned]))^(1/3)
Units: dmn1

see excel - used to set initial backlog so that work pressure gives
the initial amount of overtime, and logit model gives the correct
allocation btw types of work

Initial Capacity=
185000
Units: hours/Year

Initial DCR with Proportional Allocation[Type,Category]=
Initial Fraction of Hours by Type and Category[Type,Category]*Initial Total Desired Completion
Rate
Units: hours/Year

Initial Defect Creation from Collateral Damage[Category]= INITIAL(
Total Defect Creation from Collateral Damage[Category])
Units: Defects/Year

Initial Defect Creation Rate[Category]=
Initial Repair WO Rate[Category]*Initial Defects Elim per WO[Repair]+Initial Planned WO Rate
[Category]*Initial Defects Elim per WO[Planned]
Units: Defects/Year

Initial Defects[Category]=
Initial Defect Creation Rate[Category]*Initial Years of Accumulated Defects[Category
]
Units: Defects
Calculated by setting breakdowns=Total Workorders Closed, and Solving
for Defects

Initial Defects Elim per WO[Type]=
Reference Defects per WO[Type]*Table for Effect of Work Quality on Defects Elim per WO
(1/Initial Productivity Multiplier)
Units: Defects/workorder

Initial Desired Completion Rate[Type,Category]=
(ln(Initial Attractiveness by Type[Type])*365/alpha)*Initial Fraction of Hours by Category
[Type,Category]
Units: hours/Year

Initial Desired Completion Rate by Type[Type,Category]=
Initial Total Desired Completion Rate*Initial Fraction of Workorders by Type and Category
[Type,Category]
Units: hours/Year

Initial Effects on NDC[Category]= INITIAL(
Effects on New Defect Creation[Category])
Units: dmn1

Initial Endogenous openend WOs[Type,Category]= INITIAL(
Endogenous Opened WOs[Type,Category])
Units: workorders/Year

Initial Energy Requirements by Item[Category,EnergyType]=
Initial Energy Requirements from Buildings[EnergyType]*GSF by Energy Type[EnergyType]

] *Contribution to Bldg System Energy Requirements by energy type[Category
,EnergyType]
Units: mBTU/Year

Initial Energy Requirements from Buildings[EnergyType]=TABBED ARRAY(
0.0898 0.0634 0.1428
)
Units: mBTU/Year/GSF

Initial Fraction of Hours by Category[Type,Category]=
Initial Hours by Type and Category[Type,Category]/SUM(Initial Hours by Type and Category
[Type,Category!])
Units: dmnl

Initial Fraction of Hours by Type[Type]=
zidz(SUM(Initial Hours by Type and Category[Type,Category!]),SUM(Initial Hours by Type and
Category
[Type!,Category!]))
Units: dmnl

Within each category, what fraction are by type?

Initial Fraction of Hours by Type and Category[Type,Category]=
Initial Hours by Type and Category[Type,Category]/SUM(Initial Hours by Type and Category
[Type!,Category!])
Units: dmnl

Initial Fraction of Work to Repair= INITIAL(
SUM(Fraction of Work by Type and Category[Repair,Category!]))
Units: dmnl

Initial Fraction of Workorders by Type and Category[Type,Category]=
Initial WO Rate[Type,Category]/SUM(Initial WO Rate[Type!,Category!])
Units: dmnl

Initial GC Stock by Category[Category]= INITIAL(
Good Condition Inventory by Category[Category])
Units: \$

Initial Hours by Type and Category[Type,Category]=
zidz(Initial WO Rate[Type,Category],Base Productivity[Type,Category])
Units: hours/Year

Initial Hours Worked on Work Orders=
Initial Work Capacity+Initial Overtime Hours
Units: hours/Year

Initial Internal Budget= INITIAL(
Current Cost of Mandatory Work with Base Planned)
Units: \$/Year

Initial Items in Good Condition[Item]=
IF THEN ELSE(Initial Renewal Year by Item[Item]>= 2006,1,0)
Units: dmnl

Initial Items Needing Renewal[Item]=
IF THEN ELSE(Initial Renewal Year by Item[Item]<2006,1,0)

Units: dmn1

Initial NR Stock by Category[Category]= INITIAL(
Needs Renewal Backlog by Category[Category])

Units: \$

Initial Overtime Hours=

10108.8

Units: hours/Year

Initial overtime hours per person= INITIAL(
Overtime Hours*years per workweek/Labor Force)

Units: hours/week/people

Overtime Hours*years per workweek/Labor Force

Initial Overtime Multiplier= INITIAL(
1+(Initial Overtime Hours/Work Capacity))

Units: dmn1

Initial Planned Allocation[Category]= INITIAL(
Indicated Discretionary PM Allocation[Category])

Units: dmn1

Initial Planned extra capacity=

0

Units: hours/Year

Initial Planned WO Rate[Category]=TABBED ARRAY(
1150.25 6 938.35 5467.65 1810.75 0
)

Units: workorders/Year

Initial Productivity Multiplier=
Table for Effect of Productivity(Initial Work Pressure)

Units: dmn1

Initial Renewal Year by Item[Item]=
GET XLS CONSTANTS('Data for vensim.xls' , 'Renewals' , 'F2*')

Units: Year

Initial Repair WO Rate[Category]=TABBED ARRAY(
8907.9 6330 9588.6 30672.5 15825 0
)

Units: workorders/Year

Initial Required Staff= INITIAL(
Minimum Staff Level to Complete Mandatory Work)

Units: ppl

Initial Sales WO Rate[Category]=TABBED ARRAY(
0 8920 0 0 0 0
)

Units: workorders/Year

Initial Sales Workorder Rate=
INITIAL(Sales Opened Workorders)

Units: workorders/Year

Initial Staff Level=
100

Units: ppl
98.64

Initial target overtime fraction=
0.0543

Units: dmn1

INITIAL TIME = 2005

Units: Year
The initial time for the simulation.

Initial Time Overdue[Item]=
0

Units: years

Initial Total Desired Completion Rate=
Initial Work Capacity*Initial Work Pressure

Units: hours/Year

Initial WO Rate[Repair,Category]=
Initial Repair WO Rate[Category]

Initial WO Rate[Sales,Category]=
Initial Sales WO Rate[Category]

Initial WO Rate[Planned,Category]=
Initial Planned WO Rate[Category]

Units: workorders/Year

Initial Work Capacity=

Average Hours per week per person*Initial Staff Level/years per workweek

Units: hours/Year

Initial Work Pressure=

lookup invert(Table for Effect of Hours Charged,Initial Overtime Multiplier)

Units: dmn1

Initial Years of Accumulated Defects[Category]=

Base Initial Years of Accumulated Defects[Category]*Initial Accumulated Defects Factor

Units: years

Intensity of Use[Category]=

zidz(Defects[Category],Reference Defects[Category])

Units: dmn1

Interest earned on return from energy=

Cumulative Return from Reduced Energy Use with interest earned*Discount Rate

Units: \$/Year

Interest rate for allocation and investment decisions=

0.05

Units: 1/Year

Internal Budget=

Base Internal Budget+Additional Budget from Policies
Units: \$/Year

Internal Budget Growth Rate=
0
Units: 1/Year

Internal Budget on Workorders=
Internal Budget-Other Costs
Units: \$/Year

Internal Spending on Renewal=
Internal Surplus Resources*Switch for Internal Spending on Renewal
Units: \$/Year

Internal Spending on Renewals Real Dollars=
Internal Spending on Renewal*Conversion factor for renewal spending
Units: \$/Year

Internal Surplus Resources=
delay1(Internal Budget on Workorders*(Fraction of Potential Staff available for renewal
)
,Time to implement internal surplus resources)+Resources from Internal Unused Hours
Units: \$/Year

Internal Work Hours unused=
MAX(0,Total Hours Charged per Year-SUM(Hours on Workorders by Type and Category
[Type!,Category!]))
Units: hours/Year

Item:
(Item1-Item7500)

Item Category Weight in Energy Savings[Item,AB]=
GET XLS CONSTANTS('Data for vensim.xls' , 'Renewals' , 'P2*')
Item Category Weight in Energy Savings[Item,C]=
0
Item Category Weight in Energy Savings[Item,D2]=
0
Item Category Weight in Energy Savings[Item,D3]=
GET XLS CONSTANTS('Data for vensim.xls' , 'Renewals' , 'Q2*')
Item Category Weight in Energy Savings[Item,D45]=
GET XLS CONSTANTS('Data for vensim.xls' , 'Renewals' , 'R2*')
Item Category Weight in Energy Savings[Item,Other]=
0
Units: dmnl

Labor Cost=
Variable Labor Cost
Units: \$/Year

Labor Cost By Type[Type]=
Fraction of Work by Type[Type]*Labor Cost
Units: \$/Year

Labor Cost per Hour=

Base Labor Cost per Hour*Wage Inflation Multiplier
Units: \$/hour

Labor Force= INTEG (
Hiring-Attrition-Layoffs,
Initial Staff Level)

Units: ppl
The number of mechanics who work on work orders

Labor hours on orders closed=
SUM(Hours on Workorders by Type and Category[Type!,Category!])
Units: hours/Year

Layoffs=
MAX(0,-Adjustment for Staff-Expected Attrition)
Units: ppl/Year

Leaving Overdue Stock[Item]=
Rate of Renewal[Item]*(Time Overdue[Item])+Update to Time Since Last Renewal[Item]
]*Rate of Renewal[Item]*TIME STEP
Units: Year/Year

Lifetime by Item[Item]=
GET XLS CONSTANTS('Data for vensim.xls' , 'Renewals' , 'H2*')
Units: Year

Maintenance and Renewal Spending=
Total Renewal Spending+Maintenance Spending+Internal Spending on Renewal
Units: \$/Year

Maintenance Budget Pressure=
smooth(Current Budget Pressure,Time to perceive Budget Pressure)
Units: dmdl

Maintenance Renewal and Energy Spending=
Maintenance and Renewal Spending+Energy Spending
Units: \$/Year

Maintenance Spending=
Labor Cost+Total Materials Cost+Other Costs
Units: \$/Year

Maintenance Spending on Renewal=
Total Renewal Cost from Planned Maintenance+Total Renewal Cost from Repair
Units: \$/Year

Mandated Planned Hours=
Base Mandated PM+RAMP(Increase in Planned Hours Ramp,Planned Increase Ramp Start Time
, Planned Increase Ramp End Time)
Units: hours/Year

Mandatory Desired Completion Rate in Hours[Repair,Category]=
Desired Completion Rate in Hours at Current Productivity[Repair,Category]
Mandatory Desired Completion Rate in Hours[Sales,Category]=
Desired Completion Rate in Hours at Current Productivity[Sales,Category]
Mandatory Desired Completion Rate in Hours[Planned,Category]=

Current Mandatory Planned Hours by Category[Category]
Units: hours/Year

Mandatory Desired Completion Rate in Hours at Expected Productivity[Repair,Category]
]=

Desired Completion Rate in Hours at Expected Productivity[Repair,Category]
Mandatory Desired Completion Rate in Hours at Expected Productivity[Sales,Category]
]=

Desired Completion Rate in Hours at Expected Productivity[Sales,Category]
Mandatory Desired Completion Rate in Hours at Expected Productivity[Planned,Category]
]=

Current Mandatory Planned Hours by Category[Category]
Units: hours/Year

Markup from Hard Costs=
2

Units: dmnl

Materials Cost by Type[Type]=
Total Rate of Orders Closed by Type[Type]*Materials Cost Including Inflation[Type]
]

Units: \$/Year

Materials Cost Including Inflation[Type]=
Base Materials Costs[Type]*Materials Inflation Multiplier

Units: \$/workorder

Materials Inflation Multiplier= INTEG (
Change in Inflation Multiplier,
1)

Units: dmnl

Materials Rate of Inflation=
0

Units: 1/Year

Maximum Budget Growth Rate=
0.5

Units: 1/Year

Maximum Budget Increase=
Base Internal Budget*Maximum Budget Growth Rate

Units: \$/Year/Year

Maximum Completion Rate[Type,Category]=
(Backlog[Type,Category]/Minimum Time to Close Work Orders)

Units: workorders/Year

The maximum completion rate. Included as a first order control on
the stock of backlog.

Maximum Desired Staff on Defects=
Minimum Staff Level to Complete Mandatory Work+Maximum desired staff on planned work
above mandatory

Units: ppl

Maximum Desired Staff on Planned Work=

$$\frac{\text{(Total Maximum Planned Hours on Defects)}}{\text{Average Hours per week per person}} \times \text{years per workweek}$$
 Units: people

Maximum desired staff on planned work above mandatory=

$$\text{Maximum Desired Staff on Planned Work} - \text{Minimum Staff Level to Complete Mandatory Work}$$
 Units: people

Maximum Energy Requirements[EnergyType]=

$$\text{Maximum mBTU per gsf[EnergyType]} \times \text{GSF by Energy Type[EnergyType]}$$
 Units: mBTU/Year

Maximum Energy Requirements by Category and Type[Category,EnergyType]=

$$\text{Maximum Energy Requirements[EnergyType]} \times \text{Contribution to Bldg System Energy Requirements by energy type [Category,EnergyType]}$$
 Units: mBTU/Year

Maximum Hours on Defects by Category[Category]=

$$\frac{\text{zidz(Maximum Planned Workorder Rate[Category], Expected Productivity for planning [Planned,Category])}}{\text{[Planned,Category]}}$$
 Units: hours/Year

Maximum Internal Budget to Date= INTEG (
 Update to Maximum budget to date,
 Initial Internal Budget)
 Units: \$/Year

Maximum mBTU per gsf[EnergyType]=
 0.249,0.865,0.806
 Units: mBTU/Year/square feet

Maximum Planned Workorder Rate[Category]=

$$\frac{\text{(Defects[Category]/Minimum Time to Discover Defects Proactively)}}{\text{Reference Defects per WO [Planned]}}$$
 Units: workorders/Year

Maximum Rate of Defect Elimination[Category]=

$$\frac{\text{Defects[Category]}}{\text{Minimum Time to Eliminate Defects}}$$
 Units: Defects/Year

Maximum spending on planned work by category[Category]=

$$\text{Maximum Planned Workorder Rate[Category]} \times \text{Current Cost per WO by type and category [Planned,Category]}$$
 Units: \$/Year

Min Energy Requirements after renewal[Category]=

$$\text{SUM(Minimum mbtu after renewal[Category,EnergyType!])}$$
 Units: mBTU/Year

Min Energy Requirements after Routine Maintenance[Category]= INITIAL(

$$\text{Total Energy Requirements by Category[Category]} - \text{MAX}(0, (\text{Total Energy Requirements by Category [Category]}) \times \text{Fraction of Maintenance Savings Achievable through routine maintenance [Category]})$$
 Units: mBTU/Year

Minimum Desired budget=
MIN(Current Maximum Spending,Maximum Internal Budget to Date)
Units: \$/Year

Minimum mbtu after renewal[Category,EnergyType]=
Minimum mBtu per GSF[EnergyType]*GSF by Energy Type[EnergyType]*Contribution to Bldg
System Energy Requirements by energy type
[Category,EnergyType]
Units: mBTU/Year

Minimum mBtu per GSF[EnergyType]=
Initial Energy Requirements from Buildings[EnergyType]*(1-Potential Energy Savings as
Percentage of Initial
[EnergyType])
Units: mBTU/GSF/Year

Minimum Required on Maintenance Renewal and Energy=
Energy Spending+Minimum Required Spending on Maintenance and Renewal
Units: \$/Year

Minimum Required Spending on Maintenance and Renewal=
Current Cost of Mandatory Work with Base Planned+Base Rate of External Planned Spending
*"\$ per Million \$"
Units: \$/Year

Minimum Staff Level to Complete Mandatory Work=
Expected Mandatory Workload/Average Hours per week per person*years per workweek
Units: people

Minimum Time to Close Work Orders=
0.04
Units: Year
The minimum amount of time needed to close a work order. Creates a
constraint on the amount of work orders that can be closed at any
time.

Minimum Time to complete Renewal=
1
Units: Year

Minimum Time to Discover Defects Proactively=
2
Units: years

Minimum Time to Eliminate Defects=
0.1
Units: Year

Minimum time to reduce energy=
1
Units: Year

Needs Renewal[Item]= INTEG (
Reaching End of Life[Item]-Rate of Renewal[Item],
Initial Items Needing Renewal[Item])

Units: dmn1

Needs Renewal Backlog by Category[Category]=
SUM(Needs Renewal Cost by Category and Item[Category,Item!])

Units: \$

Needs Renewal Cost by Category and Item[AB,Item]=
IF THEN ELSE(Category by Item[Item]=1,Needs Renewal Inventory by Item[Item],0)
Needs Renewal Cost by Category and Item[C,Item]=
IF THEN ELSE(Category by Item[Item]=2,Needs Renewal Inventory by Item[Item],0)
Needs Renewal Cost by Category and Item[D2,Item]=
IF THEN ELSE(Category by Item[Item]=3,Needs Renewal Inventory by Item[Item],0)
Needs Renewal Cost by Category and Item[D3,Item]=
IF THEN ELSE(Category by Item[Item]=4,Needs Renewal Inventory by Item[Item],0)
Needs Renewal Cost by Category and Item[D45,Item]=
IF THEN ELSE(Category by Item[Item]=5,Needs Renewal Inventory by Item[Item],0)
Needs Renewal Cost by Category and Item[Other,Item]=
IF THEN ELSE(Category by Item[Item]=6,Needs Renewal Inventory by Item[Item],0)

Units: \$

Needs Renewal Inventory by Item[Item]=
Renewal Cost by Item[Item]*Needs Renewal[Item]

Units: \$

New DCR rate from breakdowns[Category,Category2]=TABBED ARRAY(
0 0 0.05 0.05 0 0
0 0 0 0 0 0
0 0.05 0.05 0 0 0
0 0 0.05 0.05 0 0
0 0 0 0.05 0.05 0
0 0 0 0 0 0
)

Units: Defect/workorder

Nominal Total Hours Charged per day= INITIAL(
Total Desired Completion Rate with Labor)

Units: hours/Year

Normal Labor cost per hour including overtime=
Labor Cost per Hour*(1-Target Overtime fraction)+Labor Cost per Hour*Overtime Multiplier
*Target Overtime fraction

Units: \$/hour

Normal Simple Payback Time[Item]=
GET XLS CONSTANTS('Data for vensim.xls' , 'Renewals' , 'P2*')

Units: years

Normal Simple Payback Time by Item[Item]= INITIAL(
IF THEN ELSE(Normal Simple Payback Time[Item]=0,0,RANDOM NORMAL(0, 100000,
Normal Simple Payback Time
[Item] , Simple Payback Time Variance[Item] , 0)))

Units: years

NPV of Energy Savings by Item[Item]=
Total potential dollar savings by item[Item]/Interest rate for allocation and investment decisions

Units: \$

NPV of future savings=
Undiscounted Cash Flow Relative to Base Excluding Energy/Discount Rate*exp(-(Time
-INITIAL TIME)*Discount Rate)
Units: \$

NPV of future savings including energy=
Total Undiscounted Cash Flow Relative to Base/Discount Rate*exp(-(Time-INITIAL TIME
) *Discount Rate)
Units: \$

NPV of Investment excluding energy=
Cumulative NPV of Investment to Date+NPV of future savings
Units: \$

NPV of Investment Including Energy Savings=
Cumulative NPV including Energy Savings+NPV of future savings including energy
Units: \$

NPV of WO Savings[Item]=
Potential Workorder Costs Saved from Renewal by Item[Item]/Interest rate for allocation and
investment decisions
*(1-exp(-Interest rate for allocation and investment decisions*Lifetime by Item[
Item]))
Units: \$

NPV per \$ Investment excluding energy=
zidz(NPV of Investment excluding energy,Cumulative Investment)
Units: dmn1

NPV per \$ investment including energy=
zidz(NPV of Investment Including Energy Savings,Cumulative Investment)
Units: dmn1

NPV per Renewal \$ by Item[Item]=
zidz(Total NPV of savings[Item]-Renewal Cost by Item[Item],Renewal Cost by Item
[Item])
Units: dmn1

NR DCR Std Dev[Item]=
Base Defect Creation Rate by Item NR[Item]*DCR Std Dev factor
Units: Defects/Year/\$

One over Year=
1
Units: 1/Year

Ordered Priority[Item]=
VECTOR RANK(Raw Priority by Item Adjusted[Item], 1)
Units: dmn1
VECTOR RANK(Raw Priority by Item[Item], 1)

Other Costs=
1e+006
Units: \$/Year

Other Energy=
98440.2
Units: mBTU/Year
includes gas and a small amount of fuel oil

Overtime Hours=
MAX(0,Labor hours on orders closed-Capacity for Work Orders)
Units: hours/Year

Overtime Multiplier=
1.5
Units: dmnl
time and a half for overtime

Perceived Campus Condition Indicator=
smooth((Total Workorder Creation Rate/Reference Breakdown Rate,Time to Adjust to Campus
condition
,1)
Units: dmnl

Planned Hours Worked=
SUM(Hours on Workorders by Type and Category[Planned,Category!])
Units: hours/Year

Planned Increase Ramp End Time=
2009
Units: Year

Planned Increase Ramp Start Time=
2005
Units: Year

Planned Opened Workorders[Category]=
(Indicated Planned Opened Orders by Category[Category]+Workorders Still to Allocate to
Defects
*Share of additional WOs by Category
[Category])*Expected Productivity for planning[Planned,Category]
Units: workorders/Year

Planned Spending Pulse Height=
0
Units: Million\$/Year [0,200,10]

Policy Capacity Available=
smooth(Policy Planned Hours,Time to Hire for Policy)*(1-Switch for Policy Spending through
Budget
)
Units: hours/Year

Policy Planned Hours=
Hours from Policy Spending*(1-Switch for Policy Spending through Budget)
Units: hours/Year

Policy Step Amount=
0
Units: hours/Year [-1,1]

Policy Step Start Time=
2011

Units: Year

Possible Hours Funded at Current Budget and Allocation=
Internal Budget on Workorders/Expected average dollars per hour

Units: hours/Year

Potential Additional Planned Hours to fund=
Potential Additional Planned Workorders/Expected Average Productivity for hiring and planning
[Planned]

Units: hours/Year

Potential Additional Planned Workorders=
Expected Surplus for Planned Work/Expected Average Cost per WO[Planned]

Units: workorders/Year

Potential Additional Staff from Budget Surplus=
MAX(0,Potential Staff Level at Current Budget and Allocation-Maximum Desired Staff on

Defects

)

Units: people

Potential dollar savings by item by type[EnergyType,Item]=
SUM(Potential Reduction in Energy Requirements when renewed[Item,Category!,EnergyType
) * Price of Energy by Type[EnergyType]

Units: \$/Year

Potential Energy Savings as Percentage of Initial[EnergyType]=TABBED ARRAY(
0.552 0.232 0.418

)

Units: dmn1

Potential Expected Planned Hours[Planned,Category]=
MIN(Potential Additional Planned Hours to fund,Total Maximum Planned Hours on Defects
-Mandated Planned Hours)*Expected Fraction of Work by Category[Planned,Category]

Potential Expected Planned Hours[Repair,Category]=

0

Potential Expected Planned Hours[Sales,Category]=

0

Units: hours/Year

Potential hours on Workorders at current budget[Type,Category]=
Mandatory Desired Completion Rate in Hours at Expected Productivity[Type,Category
) + Potential Expected Planned Hours[Type,Category]

Units: hours/Year

Potential Operating Costs Saved from Item[Item]=
zidz(Needs Renewal Inventory by Item[Item],Simple Payback Time[Item])

Units: \$/Year

Potential Planned Hours=
Mandated Planned Hours+Expected Hours Available for Supplementary Planned Work+
Policy Planned Hours

Units: hours/Year

Potential Rate of Orders Closed[Type,Category]=

$$\frac{\text{Total Hours Charged per Year} * \text{Productivity}[\text{Type,Category}] * \text{Fraction of Work by Type and Category}[\text{Type,Category}]}{\text{Category}}$$
Units: workorders/Year

The potential rate of closed work orders, as determined by productivity and hours worked. Work is also split between priorities.

Potential Reduction in Energy Costs when Renewed[Item]=

$$\text{zidz}(\text{Renewal Cost by Item}[\text{Item}], \text{Simple Payback Time}[\text{Item}])$$
Units: \$/Year

Potential Reduction in Energy Requirements when renewed[Item,Category,EnergyType]=

$$\frac{\text{Total Potential Energy Savings from Renewal}[\text{Category,EnergyType}] * \text{Share of Potential Savings by Item}[\text{Item,Category}]}{\text{Item}}$$
Units: mBTU/Year

Potential Staff Level at Current Budget and Allocation=

$$\frac{\text{Possible Hours Funded at Current Budget and Allocation} / (\text{Average Hours per week per person} + \text{Desired overtime hours per person for planning}) * \text{years per workweek}}{\text{Item}}$$
Units: people

Potential WO costs saved from renewal by Category and Item[Category,Item]=

$$\text{Additional Defect Creation Rate by Category and Item}[\text{Category,Item}] * \text{Base Hazard Rate}[\text{Category}] * \text{Cost of workorders generated by item}[\text{Item}] * \text{Average Lifetime as Defect}[\text{Category}]$$
Units: \$/Year

Potential Workorder Costs Saved from Renewal by Item[Item]=

$$\text{SUM}(\text{Potential WO costs saved from renewal by Category and Item}[\text{Category!}, \text{Item}])$$
Units: \$/Year

Preventive Defect Resolution Multiplier=

$$\frac{1}{\text{Item}}$$
Units: dmnl

Price of Energy by Type[EnergyType]=

$$\frac{\text{Energy Price by Year}[\text{EnergyType}]}{\text{Item}}$$
Units: \$/mBTU

Price of other energy=

$$\frac{20}{\text{Item}}$$
Units: \$/mBTU

Priority by Random[Item]=

$$\frac{\text{Random Number by Item}[\text{Item}]}{\text{Item}}$$
Units: dmnl

Proactive Workorders Completed=

$$\text{Total Rate of Orders Closed by Type}[\text{Planned}]$$
Units: workorders/Year

Productivity[Type,Category]=
Base Productivity[Type,Category]*Effect of Work Pressure on Productivity
Units: workorders/hour

Project Completed[Item]=
IF THEN ELSE(Current Spending On Renewals[Item]>=Needs Renewal Inventory by Item
[Item] :AND: Needs Renewal Inventory by Item[Item]>0,1,0)
Units: dmn1

Project Completion[Item]=
(Current Spending On Renewals[Item]/TIME STEP)*Project Completed[Item]
Units: \$/Year

Project Started Boost[Item]=
IF THEN ELSE(Current Spending On Renewals[Item]>0,1e+006,0)
Units: dmn1

Quality of Parts=
Effect of Budget Pressure on Quality of Parts*Weight of Budget Pressure on Parts Quality
+Effect of Work Pressure On Quality of Parts*(1-Weight of Budget Pressure on Parts Quality
)
Units: dmn1

Random Number by Item[Item]= INITIAL(
RANDOM UNIFORM(0, 100 , 0))
Units: dmn1

Random Weight in Energy Savings[Item,Category]= INITIAL(
RANDOM NORMAL(0 , 2 , 1 , Standard Deviation of Random Effect on Energy Weight
, 1))
Units: dmn1

Rate of inflation for renewal costs=
0
Units: dmn1

Rate of New Defect Creation[Category]=
Rate of New Defect Creation from Aging[Category]*Effects on New Defect Creation
[Category]+Total Defect Creation from Collateral Damage[Category]
Units: Defects/Year
Base Rate of Defect Creation[Category]*Effect of Campus Size on
Defect Creation*Defect Growth Factor

Rate of New Defect Creation from Aging[Category]=
Base Rate of Defect Creation[Category]*Defect Growth Factor*Switch for Calculated Defect
Creation Rate
+(1-Switch for Calculated Defect Creation Rate)*Defect Creation Rate by Category
[Category]
Units: Defects/Year
Base Rate of Defect Creation[Category]*Effect of Campus Size on
Defect Creation*Defect Growth Factor

Rate of New System Creation[Item]=
0
Units: 1/Year

Rate of New Work Orders[Type,Category]=
 Endogenous Opened WOs[Type,Category]*(1-Switch for constant inflow)+Switch for constant inflow
 *Initial Endogenous openend WOs[Type,Category]
 Units: workorders/Year
 The exogenous rate of new workorders, disaggregated by priority.
 Weekly data, divided by 7 to give the rate per day.

Rate of Orders Closed[Type,Category]=
 MIN(Potential Rate of Orders Closed[Type,Category],Maximum Completion Rate[Type,Category])
 Units: workorders/Year
 Rate of orders closed with labor. This value is the minimum of the maximum completion rate and the potential completion rate. The potential completion rate is determined by staff levels and productivity.

Rate of Renewal[Item]=
 (Needs Renewal[Item]/TIME STEP)*Project Completed[Item]
 Units: 1/Year

Rate of Sales Workorders Data(
 [(2005,0)-(2020,20000)],(2005,8920),(2006,9444),(2007,11148),(2008,11064),(2019.95,13421.1))
 Units: workorders/Year

Ratio of GC to NR Defect Creation Rate=
 0.2
 Units: dmn1

Raw Priority by Item[Item]=
 IF THEN ELSE(Switch for Prioritization Rule=1,NPV per Renewal \$ by Item[Item],Priority by Random [Item])
 Units: dmn1

Raw Priority by Item Adjusted[Item]=
 (Raw Priority by Item[Item])+Project Started Boost [Item]
 Units: dmn1
 ((IF THEN ELSE(Switch for Prioritization Rule=1,Priority by Benefit Cost Ratio[Item],IF THEN ELSE(Switch for Prioritization Rule =2,Priority by Lowest Cost[Item], IF THEN ELSE(Switch for Prioritization Rule=3,Priority by Relative Time Overdue[Item], Priority by Random[Item])))*)*10+Small Random Contribution to Priority[Item])*Consider Item for Funding[Item]

Reaching End of Life[Item]=
 IF THEN ELSE(Time>=Renewal Year by Item[Item],Good Condition[Item]/TIME STEP,0)
 Units: 1/Year

Reduction in Energy Requirements by Category and type[Category,EnergyType]=
 MIN(Energy Requirements by Category and EnergyType[Category,EnergyType]/Minimum time to reduce energy ,Total Reduction in Energy Requirements from Renewal by Category and Type

[Category,EnergyType]+Reduction in Energy Requirements from Maintenance[Category,EnergyType])
 Units: mBTU/Year/Year

Reduction in Energy Requirements from Maintenance[Category,EnergyType]=
 (Energy Savings from Routine Maintenance[Category])*Share of Energy Requirements by
 EnergyType and Item
 [Category,EnergyType
]
 Units: mBTU/Year/Year

Reduction in Energy Requirements from Renwal by Item[Item,Category,EnergyType]=
 Potential Reduction in Energy Requirements when renewed[Item,Category,EnergyType
]*Rate of Renewal[Item]
 Units: mBTU/Year/Year

Reference Breakdown Rate=
 INITIAL(SUM(Workorder Creation Rate[Category!]))
 Units: workorders/Year

Reference Defects[Category]=
 Initial Defects[Category]
 Units: Defects

Reference Defects per WO[Type]=
 1
 Units: Defects/workorder

Reference Planned Productivity[Category]=TABBED ARRAY(
 0.82754 0.521739 0.770616 0.690725 0.47485 0
)
 Units: workorders/hour

Reference Price of Energy=
 22
 Units: \$/mBTU

Reference Productivity[Repair,Category]=
 Reference Repair Productivity[Category]
 Reference Productivity[Sales,Category]=
 Reference Sales Productivity[Category]
 Reference Productivity[Planned,Category]=
 Reference Planned Productivity[Category]
 Units: workorders/hour

Productivity Data - because there is overtime initially, this is the
 productivity at some level of work pressure above one. So the base
 productivity is lowered to reflect what productivity would be if WP
 were 1.

Reference Repair Productivity[Category]=TABBED ARRAY(
 0.515131 0.338901 0.519551 0.508378 0.551365 0
)
 Units: workorders/hour

Reference Sales Productivity[Category]=
 0.316

Units: workorders/hour

Relative Category Attractiveness of Planned Work[Category]=TABBED ARRAY(
0.60499 0.00463415 0.496595 0.987496 1 0
)

Units: dmnl

Relative Service Quality=

Average Time to Complete Repair Work/Desired Time to complete repair work

Units: dmnl

Remaining potential WO by Category[Category]=

MAX(0,Maximum Hours on Defects by Category[Category]-Indicated Planned Opened Orders by
Category
[Category])

Units: hours/Year

Renewal Budget=

smooth(Desired External Spending,Time to Implement External Spending)

Units: \$/Year

Renewal Cost by Item[Item]=

Base Renewal Costs[Item]*Markup from Hard Costs

Units: \$

Renewal Cost from Planned Defect Elimination[Category]=

Defect Elimination through Planned Maintenance[Category]*Fraction of Defects that require
renewal

*Renewal Cost per Defect[Category]

Units: \$/Year

Renewal Cost from Repair[Category]=

Defect Elimination Through Repair[Category]*Renewal Cost per Defect[Category]*(
1+Renewal Markup when Reactive)*Fraction of Defects that require renewal

Units: \$/Year

Renewal Cost per Defect[Category]= INITIAL(

zidz(Needs Renewal Backlog by Category[Category],Defects[Category]))

Units: \$/Defect

Renewal Markup when Reactive=

2

Units: dmnl

Renewal Year by Item[Item]= INTEG (

Update to renewal year[Item],
Initial Renewal Year by Item[Item])

Units: Year

Repair and Sales Hours Worked[Category]=

zidz(Rate of Orders Closed[Repair,Category],Productivity[Repair,Category])+zidz
(Rate of Orders Closed[Sales,Category],Productivity
[Sales,Category])

Units: hours/Year

Repair Hours Worked=

SUM(Hours on Workorders by Type and Category[Repair,Category!])
Units: hours/Year

Repair Opened Workorders[Category]=
Workorder Creation Rate[Category]*(1-Switch for Service Quality Feedback)+Switch for Service
Quality Feedback
*Effect of Service Expectations on Workorders per Defect*Workorder Creation Rate
[Category]
Units: workorders/Year

Repair Workorders Completed=
Total Rate of Orders Closed by Type[Repair]
Units: workorders/Year

Resources from Internal Unused Hours=
Surplus Hours*Expected Average Productivity for hiring and planning[Planned]*Expected
Average Cost per WO
[
Planned]
Units: \$/Year

Rounded Time overdue[Item]=
INTEGER(Time Overdue[Item])
Units: years

Sales Hours Worked=
SUM(Hours on Workorders by Type and Category[Sales,Category!])
Units: hours/Year

Sales Materials Costs=
196.3
Units: \$/workorder

Sales Opened Workorders=
Switch for Constant Sales WO Rate*Exogenous Rate of Sales Workorders(0)+(1-Switch for
Constant Sales WO Rate
) *Exogenous Rate of Sales Workorders(Time)
Units: workorders/Year

Sales Opened Workorders by Category[Category]=
Sales Opened Workorders*Fraction of Sales WOs by Category[Category]
Units: workorders/Year

Sales Workorders Completed=
Total Rate of Orders Closed by Type[Sales]
Units: workorders/Year

SAVEPER =
TIME STEP
Units: Year [0,?]
The frequency with which output is stored.

Sensitivity to Intensity by Category[Category]=
0.1,0.1,1,1,0.5,0
Units: dmm1

Share of additional WOs by Category[Category]=
 zidz(Remaining potential WO by Category[Category],SUM(Remaining potential WO by Category
 [Category!]))
 Units: dmn1

Share of Energy Requirements by EnergyType and Item[Category,EnergyType]=
 zidz(Energy Requirements by Category and EnergyType[Category,EnergyType],SUM(Energy
 Requirements by Category and EnergyType
 [Category,EnergyType!]))
 Units: dmn1

Share of Potential Savings by Item[Item,Category]=
 zidz(Weighted Contribution to Energy Savings by Item[Item,Category],total weighted
 contribution
 [Category])
 Units: dmn1
 zidz(Weighted Contribution to Energy Savings by
 Item[Item,Category,EnergyType],SUM(Weighted Contribution to Energy
 Savings by Item[Item!,Category,EnergyType]))

Simple Payback=
 IF THEN ELSE(Simple Return Excluding Energy>Size of Investment,1,0)
 Units: dmn1

Simple Payback Including Energy Savings=
 IF THEN ELSE(Simple Return Including Energy>Size of Investment,1,0)
 Units: dmn1

Simple Payback Time[Item]=
 Normal Simple Payback Time by Item[Item]*SPT multiplier
 Units: years

Simple Payback Time Variance[Item]=
 Normal Simple Payback Time[Item]/5
 Units: years

Simple Return Excluding Energy= INTEG (
 Increase in Simple Return Excluding Energy,
 0)
 Units: \$

Simple Return Including Energy= INTEG (
 Increase in Simple Return Including Energy,
 0)
 Units: \$

Simple ROI=
 zidz((Simple Return Excluding Energy-Size of Investment Including Energy Savings Reinvested
),Size of Investment Including Energy Savings Reinvested)
 Units: dmn1

Simple ROI Including Energy Savings=
 zidz(Simple Return Including Energy-Size of Investment Including Energy Savings Reinvested
 ,Size of Investment Including Energy Savings Reinvested)
 Units: dmn1

Size of Investment= INTEG (
Increase in Policy Investment,
0)

Units: \$

Size of Investment Including Energy Savings Reinvested= INTEG (
Increase in Investment Including Energy Savings,
0)

Units: \$

Spending by Category[Category]=
SUM(Spending by Category and Item[Category,Item!])

Units: \$/Year

Spending by Category and Item[AB,Item]=
IF THEN ELSE(Category by Item[Item]=1,Spending by Item[Item],0)
Spending by Category and Item[C,Item]=
IF THEN ELSE(Category by Item[Item]=2,Spending by Item[Item],0)
Spending by Category and Item[D2,Item]=
IF THEN ELSE(Category by Item[Item]=3,Spending by Item[Item],0)
Spending by Category and Item[D3,Item]=
IF THEN ELSE(Category by Item[Item]=4,Spending by Item[Item],0)
Spending by Category and Item[D45,Item]=
IF THEN ELSE(Category by Item[Item]=5,Spending by Item[Item],0)
Spending by Category and Item[Other,Item]=
IF THEN ELSE(Category by Item[Item]=6,Spending by Item[Item],0)
Units: \$/Year

Spending by Item[Item]=
ALLOCATE BY PRIORITY(Desired Renewal Spending by Item[Item], Ordered Priority[
Item] , ELMCOUNT(Item), width , Total Spending on Renewal
)

Units: \$/Year

ALLOCATE BY PRIORITY(Desired Renewal Spending by Item[Item], Ordered
Priority[Item] , ELMCOUNT(Item), width , Total Spending on Renewal
)

Spending per WO by Type[Type]=
zidz(Total Cost by Type[Type],Total Rate of Orders Closed by Type[Type])

Units: \$/workorder

SPT multiplier=
Reference Price of Energy/Current Price of Energy

Units: dmn1

Standard Deviation of Random Effect on Energy Weight=
0.1

Units: dmn1

Start of Planned Investment=
2007

Units: Year

Starting GSF=
1.2e+007

Units: square feet

2006 starting number

Starting Planned Material Costs=

23.56

Units: \$/workorder

Starting Repair Material Costs=

68.2

Units: \$/workorder

Strength of Effects on Defect Creation=

3

Units: dmn1

Surplus Hours=

MAX(0,Potential Planned Hours-Total Planned Hours on Defects)

Units: hours/Year

Switch for Additional External Spending=

1

Units: dmn1 [0,1,1]

Switch for Calculated Defect Creation Rate=

0

Units: dmn1 [0,1,1]

Switch for Collateral Damage=

1

Units: dmn1

Switch for constant inflow=

0

Units: dmn1 [0,1,1]

Switch for Constant Sales WO Rate=

0

Units: dmn1 [0,1,1]

Switch for Defect Elimination=

1

Units: dmn1 [0,1,1]

Switch for Effects on New Defect Creation=

1

Units: dmn1

Switch for Endogenous DCT=

1

Units: dmn1

Switch for Energy Reinvestment=

1

Units: dmn1 [0,1,1]

Switch for Energy Savings from Routine Maintenance=

1

Units: dmnl [0,1,1]

Switch for Exogenous Opened WOs=

0

Units: dmnl [0,1,1]

switch for exogenous outflow=

0

Units: dmnl [0,1,1]

Switch for Growing Campus=

0

Units: dmnl [0,1,1]

Switch for Internal Spending on Renewal=

0

Units: dmnl [0,1,1]

Switch for Policy Spending through Budget=

0

Units: **undefined**

Switch for Prioritization Rule=

1

Units: dmnl

1=cost benefit; other = random

Switch for proportional allocation=

0

Units: dmnl

Switch for Reinvestment=

1

Units: dmnl [0,1,1]

Switch for Service Quality Feedback=

0

Units: dmnl [0,1,1]

Switch for staff adjustment=

1

Units: dmnl [0,1,1]

1= staff adjusts to desired staff 0= staff adjusts only to attrition
(staff remains constant)

Switch for Variable Hazard Rate=

0

Units: dmnl [0,1,1]

Table for effect of budget pressure on quality of parts(

[(0,0)-(2,1.2)],(0.5,1.05),(0.788991,1.03158),(1,1),(1.27829,0.963158),(1.59021
,0.931579),(2,0.9))

Units: dmnl

Table for Effect of Hours Charged(

[(0.5,0.9)-(1.5,1.1)],(0.5,0.95),(0.8,0.975),(1,1),(1.1,1.05),(1.25,1.08),(1.5,

1.1))

Units: dmn1

Table for Effect of Intensity of Use on Defect Creation(

[(0,0.8)-(1.5,1.2)],(0,0.9),(0.178899,0.912281),(0.380734,0.929825),(0.568807,0.952632),
(0.752294,0.97193),(1,1),(1.26147,1.02632),(1.5,1.05))

Units: dmn1

Table for Effect of Perceived Campus Condition on Reporting(

[(0,0)-(5,1)],(0,1),(1,1),(2,1),(2.84404,0.833333),(3.76147,0.561404),(4.06728,
0.403509),(4.63303,0.184211),(4.98471,0.131579))

Units: dmn1

Table for Effect of Productivity(

[(0,0)-(2,2)],(0,0.85),(0.379205,0.865789),(0.75,0.9),(1,1),(1.1,1.05),(1.25,1.1),
(1.63303,1.19474),(2,1.2))

Units: dmn1

Table functions incorporate regression results in values for .75 and
1.25. Outside of this range, assumptions made about extreme
conditions.\!\!\!

Table for Effect of Service on Opened WO per Defect(

[(0,0)-(10,1)],(0,1),(1,1),(2,1),(3.57798,0.890351),(5.19878,0.815789),(7.52294,
0.517544),(8.7156,0.25),(9.96942,0.144737))

Units: dmn1

Table for Effect of Work Pressure on DCT(

[(0,0)-(3,3)],(0,0.5),(0.449541,0.565789),(0.752294,0.723684),(1,1),(1.26605,1.27632),
(1.56881,1.51316),(1.86239,1.64474),(2.33945,1.85526),(3,2))

Units: dmn1

Table for Effect of Work Pressure on Quality of Parts(

[(0,0)-(2,1.2)],(0.5,1.05),(0.788991,1.03158),(1,1),(1.27829,0.963158),(1.59021,
0.931579),(2,0.9))

Units: dmn1

Table for Effect of Work Quality on Defects Elim per WO(

[(0,0)-(2,2)],(0,0),(0.122324,0.175439),(0.287462,0.412281),(0.464832,0.614035),
(0.605505,0.77193),(0.746177,0.868421),(0.941,0.97),(1,1),(1.52294,1.09649),(1.99388,
1.15789))

Units: dmn1

Table for Effect of Work Quality on New Defect Creation(

[(0.8,0.8)-(1.3,1.2)],(0.8,1.05),(1,1),(1.3,0.925))

Units: dmn1

Target Overtime fraction=

smoothi(Desired overtime hours per person for planning/(Average Hours per week per person
+Desired overtime hours per person for planning
,time to adjust target overtime fraction,Initial target overtime fraction)

Units: dmn1

Time for Endogenous Growth=

2006

Units: Year

Time Overdue[Item]= INTEG (
Update to Time Since Last Renewal[Item]-Leaving Overdue Stock[Item],
Initial Time Overdue[Item])

Units: Year

TIME STEP = 0.015625

Units: Year [0,?]

The time step for the simulation.

Time to adjust Base budget=

1

Units: years

Time to Adjust DCT=

2

Units: years

time to adjust fraction charged=

1

Units: Day

Time to adjust Productivity Expectations=

1

Units: Year

Time to Adjust Staff=

0.5

Units: years

adjustment time for increasing the number of staff. Due to budget pressures, and historical data indicating almost constant staffing levels, this is assumed to be a very long delay

time to adjust target overtime fraction=

0.1

Units: Year

Time to Adjust to Campus condition=

2

Units: years

Time to Decrease Staff=

2

Units: years

Time constant for decreasing the size of the labor force.

Time to form Attrition Expectations=

0.2

Units: years

Time for the rate of attrition to be incorporated into expectations

Time to form expectations for hiring and planning=

0.25

Units: Year

time to form expectations for opened work=

0.5

Units: Year

Time to Hire for Policy=
0.1

Units: Year

Time to Implement External Spending=
0.5

Units: Year

Time to implement internal surplus resources=
1

Units: Year

Time to perceive Budget Pressure=
1

Units: Year

Time to perceive staff needs=
0.2

Units: Year

Time to perceive workload=
0.5

Units: Year

Time to reach Maximum Energy Requirements[EnergyType]=
40,550,100

Units: years

37,552,116

Time to reinvest energy savings=
0.25

Units: Year

Total Cost by Type[Type]=
Labor Cost By Type[Type]+Materials Cost by Type[Type]

Units: \$/Year

Total current dollar value of energy savings=
MAX(0,Base Utilities Spending-Energy Spending)

Units: \$/Year

Total Current Spending on Renewals=
SUM(Current Spending On Renewals[Item!])

Units: \$

Total DCR by Type[Type]=
SUM(Desired Completion Rate in hours[Type,Category!])

Units: hours/Year

Total Defect Creation from Collateral Damage[AB]=
Total Defect Creation from Collateral Damage by Category2[Cat1]

Total Defect Creation from Collateral Damage[C]=

Total Defect Creation from Collateral Damage by Category2[Cat2]

Total Defect Creation from Collateral Damage[D2]=

Total Defect Creation from Collateral Damage by Category2[Cat3]
 Total Defect Creation from Collateral Damage[D3]=
 Total Defect Creation from Collateral Damage by Category2[Cat4]
 Total Defect Creation from Collateral Damage[D45]=
 Total Defect Creation from Collateral Damage by Category2[Cat5]
 Total Defect Creation from Collateral Damage[Other]=
 Total Defect Creation from Collateral Damage by Category2[Cat6]
 Units: Defects/Year

Total Defect Creation from Collateral Damage by Category2[Category2]=
 SUM(Defect Creation from Collateral Damage[Category!,Category2])
 Units: Defect/Year

Total Defect Creation Rate=
 SUM(Rate of New Defect Creation[Category!])
 Units: Defects/Year

Total defect Elimination[Category]=
 Defect Elimination through Planned Maintenance[Category]+Defect Elimination Through Repair
 [Category]
 Units: Defects/Year

Total Defect Elimination Rate=
 SUM(Total defect Elimination[Category!])
 Units: Defect/Year

Total Defects=
 SUM(Defects[Category!])
 Units: Defects

Total Desired Completion Rate with Labor=
 SUM(Desired Completion Rate in hours[Type!,Category!])
 Units: hours/Year

Total Effective Renewal Spending=
 Total Renewal Cost from Planned Maintenance+SUM(Effective Renewal spending on Repair
 [Category!])+Additional Proactive Spending on Renewal
 Units: \$/Year

Total Energy Cost=
 SUM(Energy Cost by Type[EnergyType!])+Other Energy*Price of other energy
 Units: \$/Year

Total Energy Requirements by Category[Category]=
 SUM(Energy Requirements by Category and EnergyType[Category,EnergyType!])
 Units: mBTU/Year

Total Energy Requirements from Buildings=
 SUM(Energy Requirements by EnergyType[EnergyType!])+Other Energy
 Units: mBTU/Year

Total Good Condition Assets=
 SUM(Good Condition Inventory by Item[Item!])
 Units: \$

Total Hours Charged per Year=

Capacity for Work Orders*Effect of Work Pressure on Hours Charged
Units: hours/Year
2386

Total Hours Worked=
Total Hours Charged per Year
Units: hours/Year

Total Materials Cost=
SUM(Materials Cost by Type[Type!])
Units: \$/Year

Total Maximum Planned Hours on Defects=
SUM(Maximum Hours on Defects by Category[Category!])
Units: hours/Year

Total NPV of savings[Item]=
NPV of Energy Savings by Item[Item]*Weight of Energy Costs in Benefit+NPV of WO Savings
[Item]*Weight of Workorders Produced in Benefit
Units: \$

Total Planned Hours on Defects=
MIN(Potential Planned Hours-Base Planned Hours on Renewals, SUM(Maximum Hours on
Defects by Category
[Category!]))
Units: hours/Year

Total potential dollar savings by item[Item]=
SUM(Potential dollar savings by item by type[EnergyType!,Item])
Units: \$/Year

Total Potential Energy Savings from Renewal[Category,EnergyType]=
MAX(0,Energy Requirements by Category and EnergyType[Category,EnergyType]-Minimum
mbtu after renewal
[Category,EnergyType
)
Units: mBTU/Year

Total Rate of Orders Closed by Category[Category]=
SUM(Rate of Orders Closed[Type!,Category])
Units: workorders/Year

Total Rate of Orders Closed by Type[Type]=
SUM(Rate of Orders Closed[Type,Category!])
Units: workorders/Year

Total Rate of Renewal=
SUM(Rate of Renewal[Item!])
Units: 1/Year

Total Reduction in Energy Requirements from Renewal by Category and Type[Category
,EnergyType]=
SUM(Reduction in Energy Requirements from Renwal by Item[Item!,Category,EnergyType
)
Units: mBTU/Year/Year

Total reductions[EnergyType]= INTEG (increase in total reductions[EnergyType], 0)

Units: mBTU/Year

Total Renewal Backlog= SUM(Needs Renewal Inventory by Item[Item!])

Units: \$

Total Renewal Cost from Planned Maintenance= SUM(Renewal Cost from Planned Defect Elimination[Category!])

Units: \$/Year

Total Renewal Cost from Repair= SUM(Renewal Cost from Repair[Category!])

Units: \$/Year

Total Renewal Spending= Additional Proactive Spending on Renewal+Maintenance Spending on Renewal

Units: \$/Year

Total Spending on Proactive Work= Total Cost by Type[Planned]

Units: \$/Year

Total Spending on Renewal= Total Effective Renewal Spending+Internal Spending on Renewals Real Dollars

Units: \$/Year

Total Spending on Renewals= SUM(Increase in Current Spending on Renewals[Item!])

Units: \$/Year

Total Spending on Repair= Total Cost by Type[Repair]

Units: \$/Year

Total Spending on Sales= Total Cost by Type[Sales]

Units: \$/Year

Total Spending per GSF= Maintenance and Renewal Spending/Gross Square Feet Maintained

Units: \$/Year/GSF

Total Undiscounted Cash Flow Relative to Base= Base Spending Including Utilities-Maintenance Renewal and Energy Spending

Units: \$/Year

total weighted contribution[Category]= SUM(Weighted Contribution to Energy Savings by Item[Item!,Category])

Units: \$

Total Workorder Creation Rate= SUM(Workorder Creation Rate[Category!])

Units: workorders/Year

Type:

Repair,Sales,Planned

Undiscounted Cash Flow Relative to Base Excluding Energy=

Base Maintenance and Renewal Annual Spending-Maintenance and Renewal Spending

Units: \$/Year

Update to Maximum budget to date=

IF THEN ELSE(Base Internal Budget>Maximum Internal Budget to Date,(Base Internal Budget
-Maximum Internal Budget to Date)/TIME STEP,0)

Units: \$/Year/Year

Update to renewal year[Item]=

Rate of Renewal[Item]*(Lifetime by Item[Item]+Rounded Time overdue[Item])

Units: Year/Year

Update to Time Since Last Renewal[Item]=

Needs Renewal[Item]*Aging per year

Units: Year/Year

Variable Labor Cost=

(Labor hours on orders closed-Overtime Hours)*Labor Cost per Hour+Overtime Hours

*Labor Cost per Hour*Overtime Multiplier

Units: \$/Year

Wage Inflation Multiplier= INTEG (

Change in Wage multiplier,
1)

Units: dmnl

Wage Rate of Inflation=

0

Units: 1/Year

weeks per year=

52

Units: weeks/Year

Weight of Budget Pressure on Parts Quality=

0.8

Units: dmnl

Weight of Energy Costs in Benefit=

base energy weight + STEP(Energy Weight Step,Energy Weight Step time)

Units: dmnl

Weight of Workorders Produced in Benefit=

1

Units: dmnl

Weighted Contribution to Energy Savings by Item[Item,Category]=

Weighted Cost for Contribution to Potential Energy Savings[Item]*Item Category Weight in
Energy Savings

[Item,Category]*Random Weight in Energy Savings[Item,Category]

Units: \$

Weighted Cost for Contribution to Potential Energy Savings[Item]=
Needs Renewal Inventory by Item[Item]+Good Condition Inventory by Item[Item]*Good
Condition Discount Factor in Added Energy Costs
Units: \$

Weighted Cost per WO[Type,Category]=
Expected Cost per WO by type and Category[Type,Category]*Expected Fraction of Work by
Category
[Type,Category]
Units: \$/workorder

Weighted dollars per hour at expected work allocation[Type,Category]=
Expected Cost per WO by type and Category[Type,Category]*Expected Fraction of Hours by
Type and Category
[Type,Category]*Expected Productivity for hiring and planning[Type,Category]
Units: \$/hour

Weighted Expected Productivity[Type,Category]=
Expected Productivity for hiring and planning[Type,Category]*Expected Fraction of Work by
Category
[Type,Category]
Units: workorders/hour

Weighted Expected Productivity 0[Type,Category]=
Expected Productivity for planning[Type,Category]*Expected Fraction of Work by Category 0
[Type,Category]
Units: workorders/hour

Weighted Hours Creation Rate[Category]=
Work Hours Creation Rate[Category]*Relative Category Attractiveness of Planned Work
[Category]
Units: hours/Year

width=
0.5
Units: dmn1

WO cost Std Deviation Factor=
0.4
Units: dmn1

Work Capacity=
Average Hours per week per person*Full Time Employees/years per workweek
Units: hours/Year

Work Hours Creation Rate[Category]=
zidz(Workorder Creation Rate[Category],Base Productivity[Repair,Category])
Units: hours/Year

Work Pressure=
Total Desired Completion Rate with Labor/Capacity for Work Orders
Units: dmn1

Work pressure is the desired completion rate divided by the normal
completion rate.

Work Quality[Type]=
Base Productivity[Type,AB]/Productivity[Type,AB]
Units: dmnl

Workorder Cost Std Deviation[Item]=
Base Cost per WO by Item[Item]*WO cost Std Deviation Factor
Units: \$/workorder
50

Workorder Creation Rate[Category]=
Defects[Category]*Base Hazard Rate[Category]
Units: workorders/Year

Workorders Still to Allocate to Defects=
MAX(0,Total Planned Hours on Defects-SUM(Indicated Planned Opened Orders by Category
[Category!]))
Units: hours/Year

Years elapsed=
MAX(0,Time-Start of Planned Investment)
Units: Year

years per workweek=
0.02
Units: years/week
1/50

Years to calculate inflation=
(Time-Base Year for Inflation)*One over Year
Units: dmnl