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Explores why profitable energy efficiency investments are not made using MIT as a case study.

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We use ethnographic study, quantitative data and archival materials to develop a system dynamics simulation model of MIT's maintenance and energy use/efficiency programs.

Giving up Too Soon: Capability Traps and the Failure of Win-Win Investments in Process Improvement and Industry Self-Regulation

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Abstract

Can managers improve compliance with regulations and enhance corporate social responsibility while also improving profitability? Many scholars and practitioners argue that there are "win-win" investments that improve both regulated outcomes and the bottom line—firms can do well by doing good in domains from environmental performance, maintenance, reliability and workplace safety to financial accounting. For example, studies document the existence of numerous investments in energy efficiency that have positive NPV and short payback times. Yet research also shows many of these attractive opportunities are not taken—money is left on the table. If proactive investments are really profitable, why are they so often not done? Explanations for the puzzle include pressure for short run results from shareholders, information asymmetries, agency problems, and behavioral biases. Here we explore this puzzle using the case of energy use and maintenance in a large research university. With a large endowment, pro-social mission, long time horizon, and no short-term shareholder pressure, the institution should be ideally positioned to undertake investments in energy efficiency and pro-active maintenance that improve facility and equipment reliability and safety while lowering operating costs. Nevertheless, our research site was characterized by a large backlog of deferred maintenance, poor energy efficiency, and high expenditures for reactive maintenance. We use ethnographic field study and panel regression of building performance data to develop a simulation model integrating energy use, maintenance, and facilities renewal. We find the institution became stuck in a capability trap: higher energy and maintenance costs reduce efficiency investments and proactive maintenance, causing energy efficiency and facilities to deteriorate, and eroding capabilities for improvement, further boosting costs. We use the model to explain how the trap arose and what is required to escape it. We find that even when managers make substantial proactive investments, investments may not be large enough or long enough to cross a tipping threshold and reverse the vicious cycle. Despite the appearance of success in the short-term, performance gradually erodes to its original state, wiping out gains. Successful self-regulation and process improvement requires managers not only recognize and act on win-win opportunities, but also sustain investments beyond levels that initially appear sufficient so that the organization crosses the tipping threshold.

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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, Coglianese & 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 (Levine, Toffel & Johnson 2012, 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. Identifying win-win investments and persuading organizations to make them has become an important strategy of individuals and organizations in the corporate responsibility, 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, Amin (2011) estimates that upgrading the US electrical grid 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 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 biases. 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). The famous landlord-tenant problem arises when a property owner faces difficulty passing on the costs of an investment to a tenant, and so under-invest (Jaffe & Stavins 1994). Lastly, behavioral biases 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 surely have merit, they are only partly satisfactory. Certainly, principal-agent problems, information asymmetries, management biases and short-termism 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. For example, organizations often undertake investments in infrastructure, technology and process improvement yet only some achieve the productivity, reliability and safety 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 building maintenance and energy use 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 determines 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 may easily under-invest, 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. With a large endowment, pro-social mission, long time horizon, and no short-term shareholder pressure, the institution should be ideally positioned to undertake investments in energy efficiency and pro-active maintenance that improve facility and equipment reliability and safety while lowering operating costs. For several reasons, building maintenance is an excellent setting to study possible alignment between regulated outcomes, social responsibility, and the bottom line. First, as the owner-operator of its facilities, MIT does not face the landlord-tenant agency problems that can thwart proactive investment. Second, building maintenance is an area where clear best practices are known to improve reliability and ultimately profitability (e.g. Moubray 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 yet might have been prevented by a simple inspection and part replacement.

Despite conditions favoring a long-term outlook and proactive investment, 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, the university 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.

We next describe in more detail how the various data sources are triangulated into a model of the maintenance organization. We then use the model to analyze the dynamics of proactive investments in routine maintenance and energy efficiency.

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.

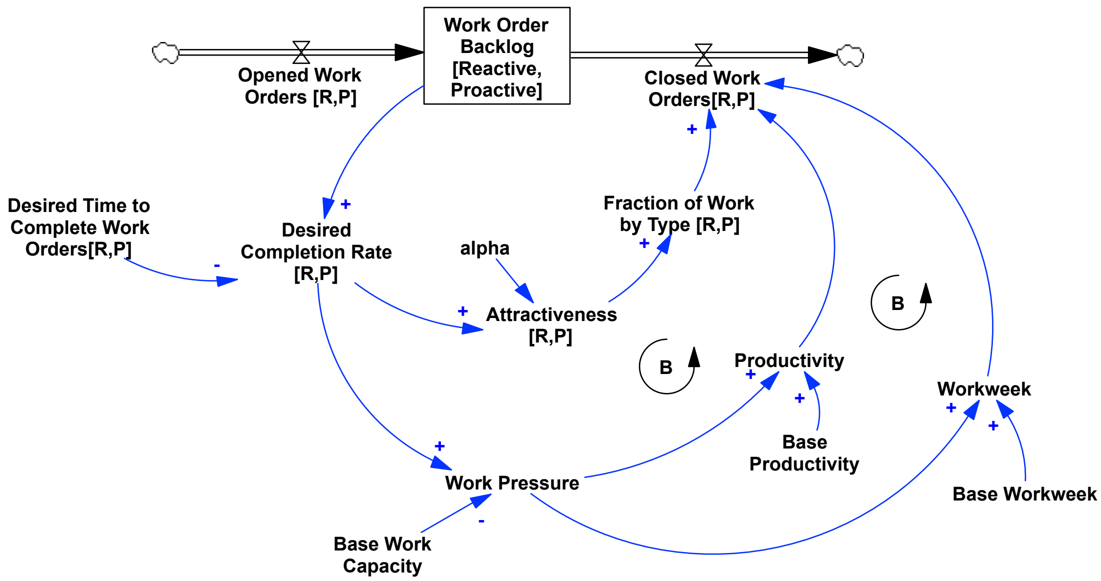

Figure 1: Basic Structure of a Labor Capacitated Process

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:

$$f_i = \frac{A_i}{\sum_j A_j} \tag{2}$$

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

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. The flow 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.

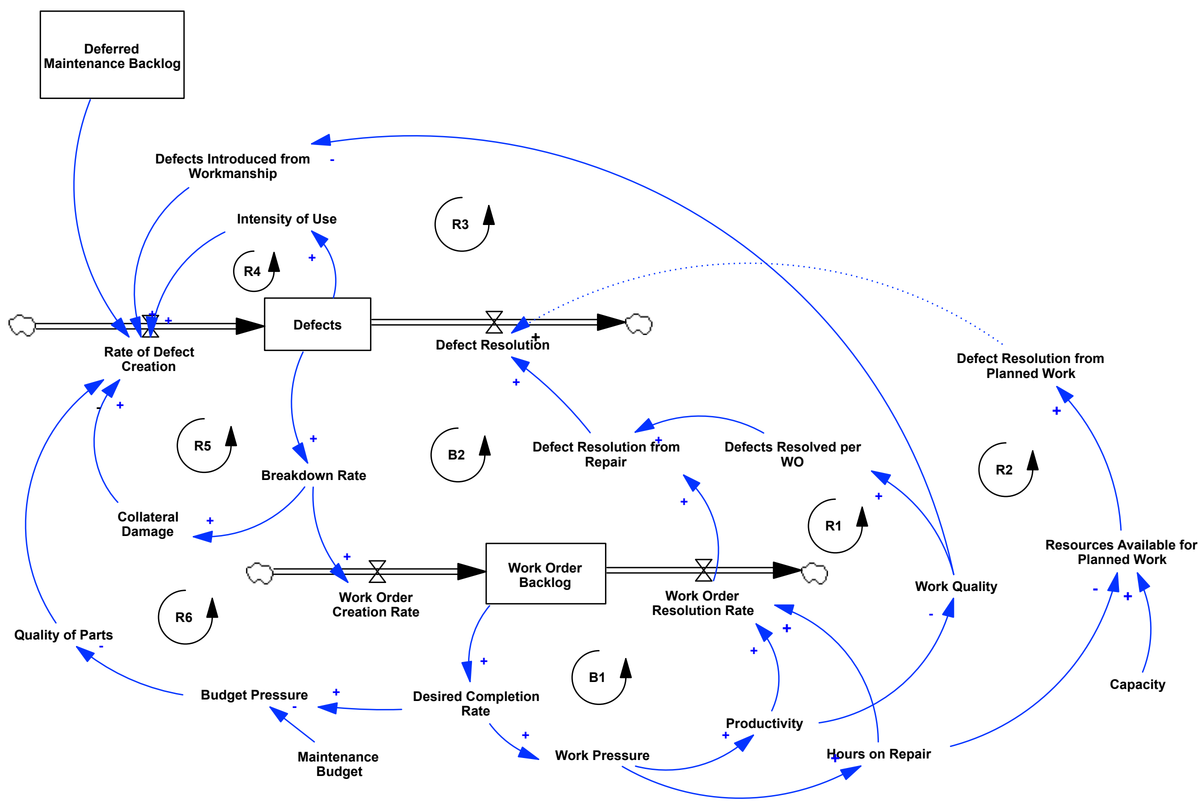

Figure 2: Feedback Relationships Introduced through Equipment Defects

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:

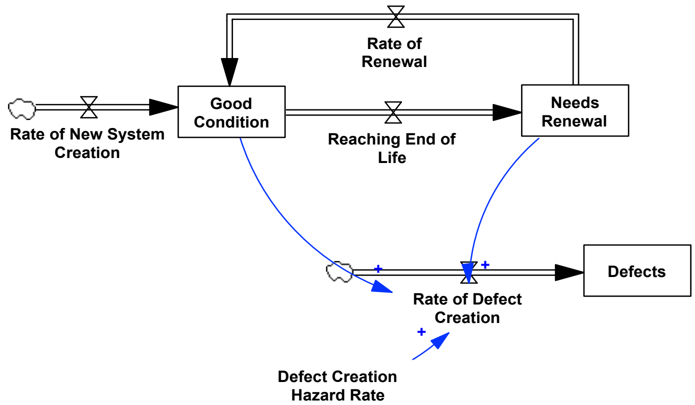

Figure 3: Stock and Flow Structure for Infrastructure Renewal

Each building system is categorized as either being in *good condition* or *needs renewal*. Systems reaching the end of their useful life age from the good condition stock to the needs renewal stock. System renewal restores them 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:

$$R_{b,c} = \sum_{i}^{i \in G,c} i h_G \varepsilon_i + \sum_{j}^{j \in N,c} j h_N \varepsilon_j \tag{6}$$

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.

Defect creation, in turn, is influenced by several factors described above and shown in Figure 2. We formulate these effects as follows:

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

where Q_p is parts quality, Q_w is 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 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, furniture, lab equipment and flooring.

Although the rate of renewal investment at the university is far too low to address all items needing 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. (The appendix details the building fixed effects.)

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:

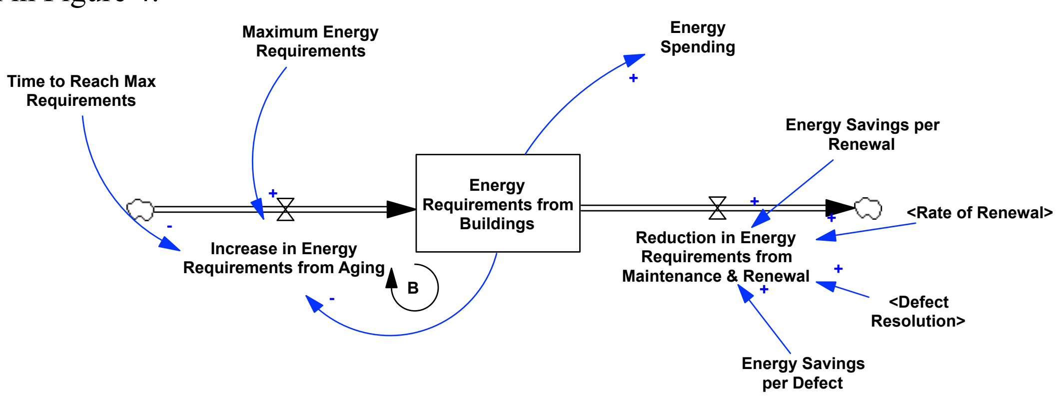

Figure 4: Stock and Flow Structure of Building Energy Requirements

We next estimate the parameters E* and τ for each of the three forms of energy. 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 (details are in 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 undertaken. We look to literature on building commissioning to obtain estimates on the 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 allocate potential savings among building systems, based on the judgment of an expert engineer.

Model Analysis

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.

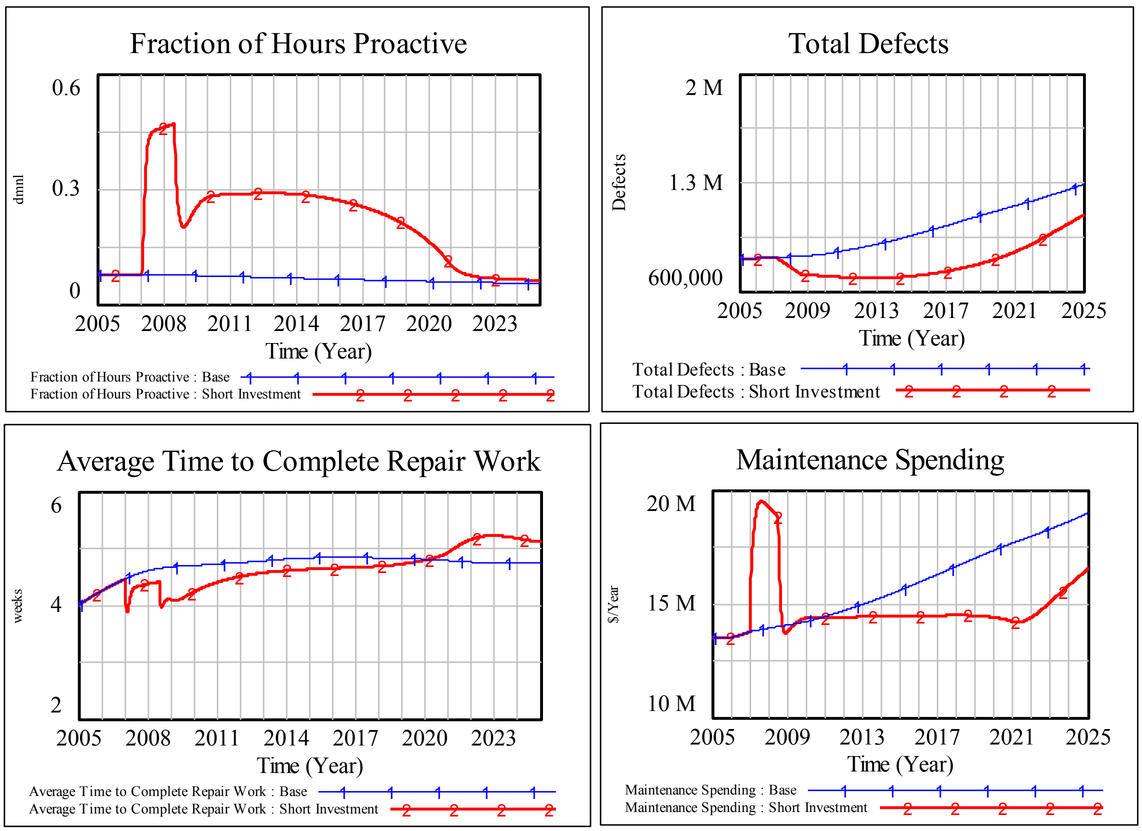

Figure 5: Comparing the base run with a proactive investment of $9M over a total of two years

Figure 5 also 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.

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 decade these gains are gradually lost. To understand why, consider the stock of defects shown in Figure 2. Proactive investment leads to a drop in defects during between 2007 and 2009. The drop in defects decreases the breakdown rate, reduces the fraction of time spent on reactive work, increases the fraction of time spent on planned work, and thus increases the 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. The rising inflow to the stock of defects – a result of underinvestment in renewals – speeds the decay of the system.

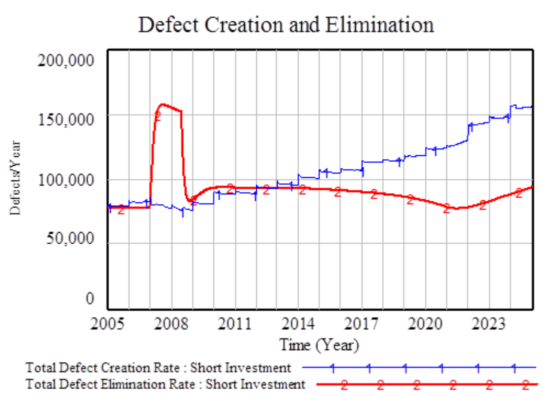

Figure 6: Comparison of defect creation and defect elimination for the run "Short Investment"

Despite the return of the organization to near previous levels of disrepair, however, the policy is financially successful. We calculate the NPV of the investment by comparing discounted total spending between the base run and the policy run. The policy yields a NPV of $25M relative to the base; other investments of a similar size and duration perform similarly. When energy savings are included, the NPV is greater still, rising to $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 the 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.

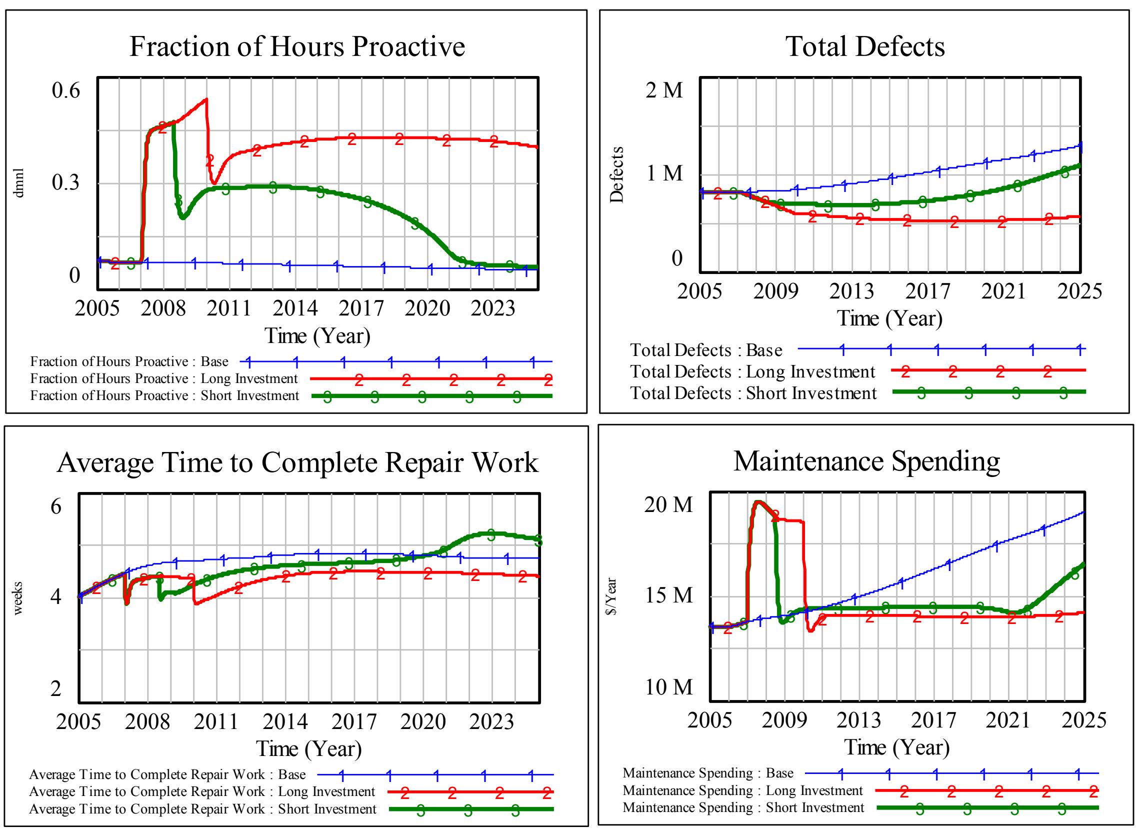

Figure 7: Comparison of a Short and Longer Investment

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.).

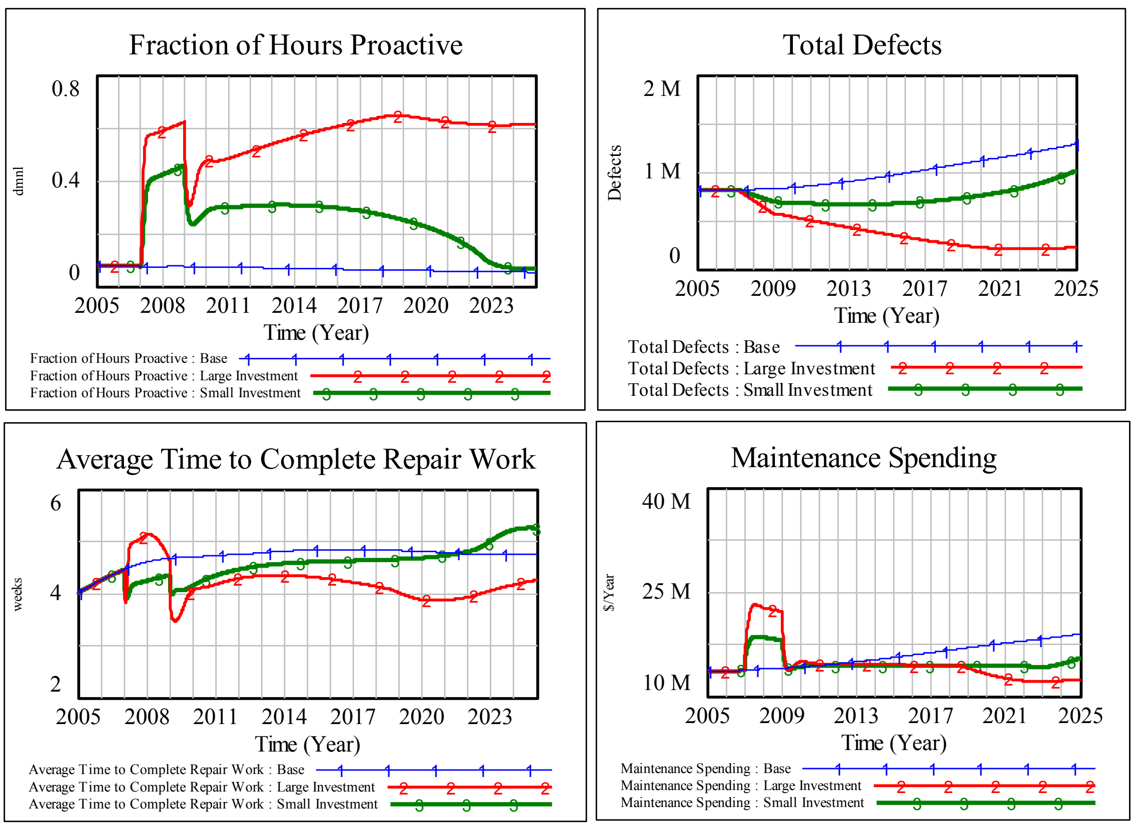

Figure 8: Comparison of a Small and Larger Investment

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. Table 3 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%

Table 3: 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 9 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.

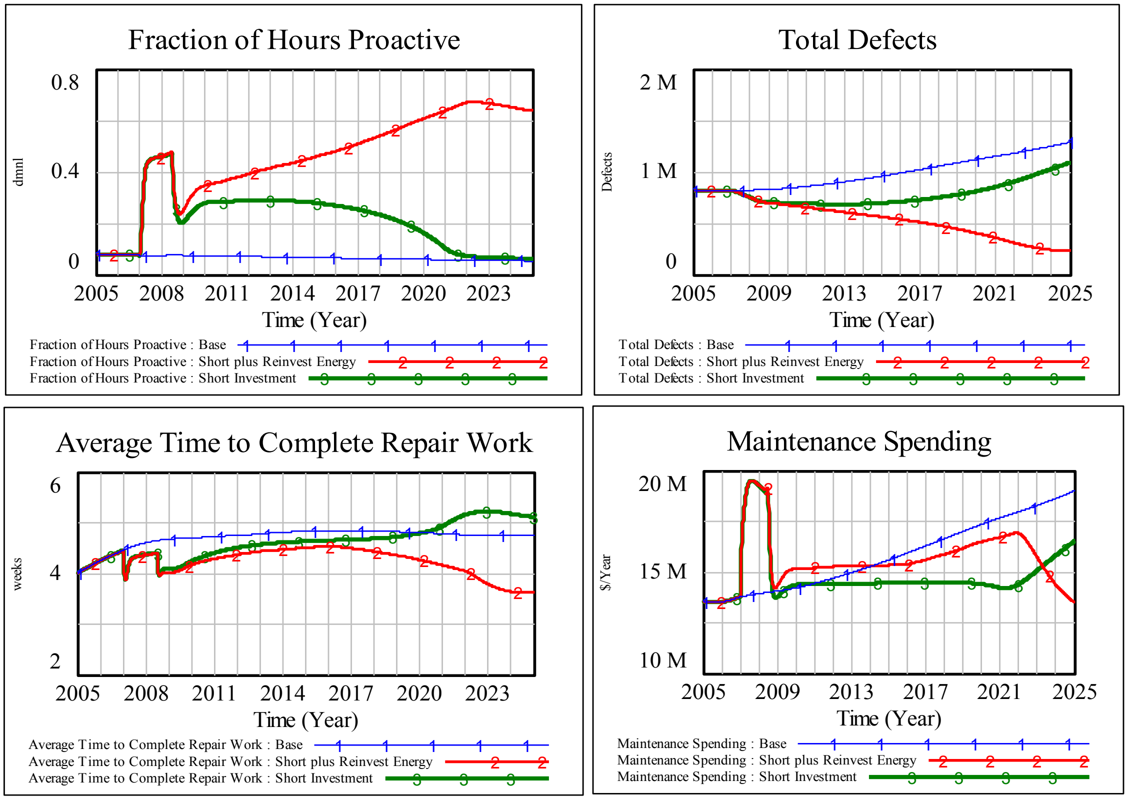

Figure 9: Reinvesting Energy Savings

Table 3 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.

Table 3 shows 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 offer high NPV, 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 10 shows the sensitivity of model results to a change in the strength of positive feedbacks R3, R4, and R6. To do so we adjust the slope of the functions *f, g*, and *h* in equation (7). For example, a flatter slope in *f* means that an increase in parts quality causes a smaller drop in the rate of defect creation. Results show that weaker positive feedback can speed the return of reactive work, or even prevent the system from tipping into the virtuous regime. Although the two runs in Figure 10 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 reinforcing feedbacks.

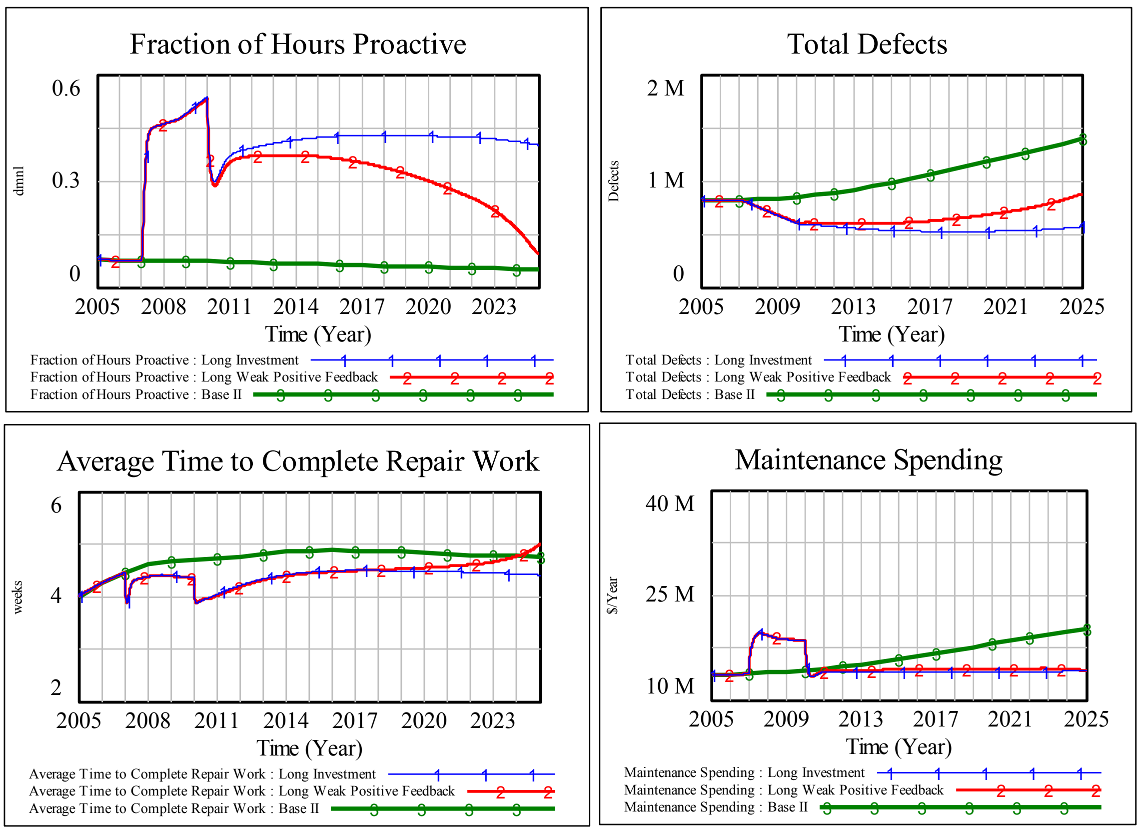

Figure 10: Weakening the strength of Positive Feedback

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 scholarly research and practical action.

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. 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.

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.

Coglianese, C., and J. Nash. 2001. *Regulating from the inside: can environmental management systems achieve policy goals?* Washington, DC: Resources for the Future.

Creyts, 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. Sterman. 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.

Levine, D., M. Toffel and M. Johnson. 2012, “Randomized Government Safety Inspections Reduce Worker Injuries with No Detectable Job Loss.” *Science* 336:907-911.

Levitt, J. 2009. *Handbook of Maintenance Management*. New York, NY: Industrial Press.

Marquis, Christopher, Mary Ann Glynn, and Gerald F. Davis. 2007. “Community Isomophism 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.

Giving up Too Soon: Capability Traps and the Failure of Win-Win Investments in Process Improvement and Industry Self-Regulation

Appendix and Technical Documentation

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This document provides details on the data sources, regressions and technical details for the model. First, we outline additional assumptions for several model sectors. Second, we provide a full presentation of model sector diagrams and model equations. Finally, we provide a full listing of the model source code.

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:

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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.

$$Share_i = A_i / \sum_j A_j$$

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

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:

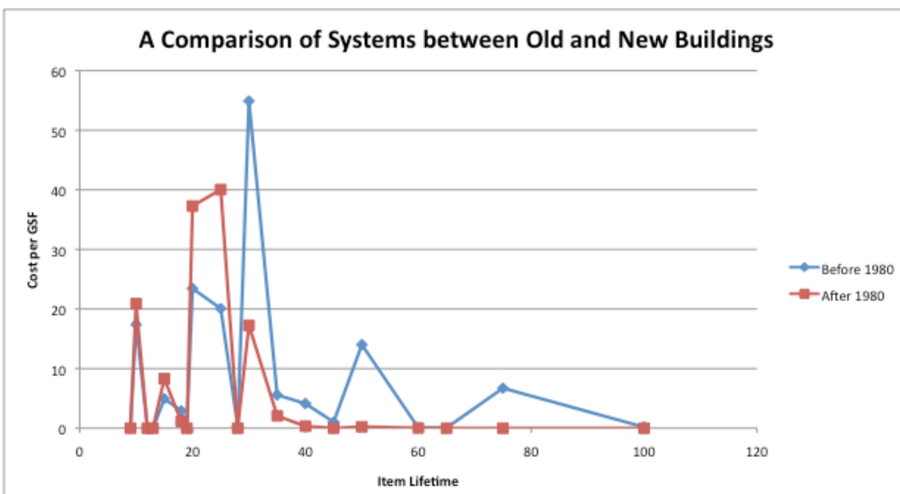


Figure 1: Comparison of Systems between Old and New Buildings

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:

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

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:

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

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

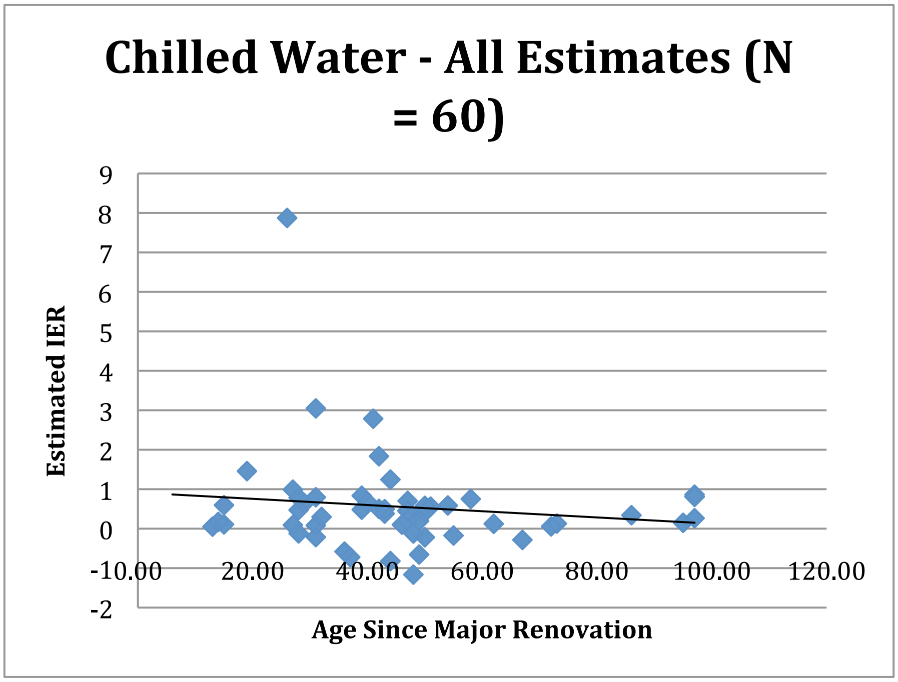
CS30	0.002829	0.0195	0.15	0.8845
CS31	0.214397	0.0195	11.01	<.0001
CS32	0.034909	0.0195	1.79	0.0737
CS33	0.048061	0.0195	2.47	0.0139
CS34	-0.0057	0.0195	-0.29	0.7697
CS35	0.063785	0.0195	3.28	0.0011
CS36	0.133321	0.0195	6.85	<.0001
CS37	0.020688	0.0195	1.06	0.2886
CS38	0.018079	0.0195	0.93	0.3536
CS39	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

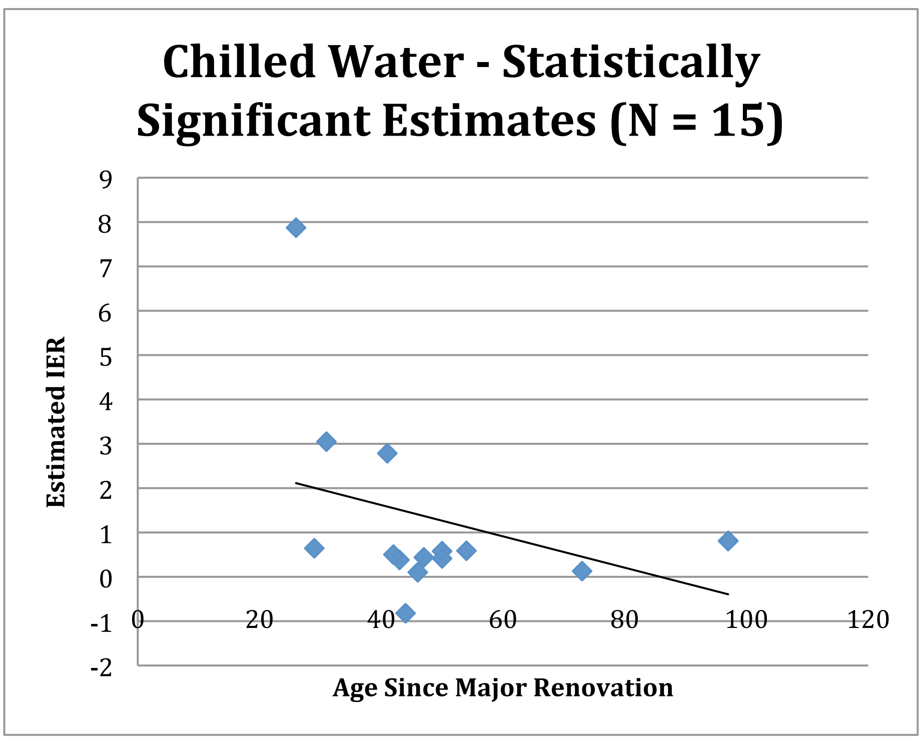
Table 5: Regression Results for the Effect of Aging on Steam Consumption

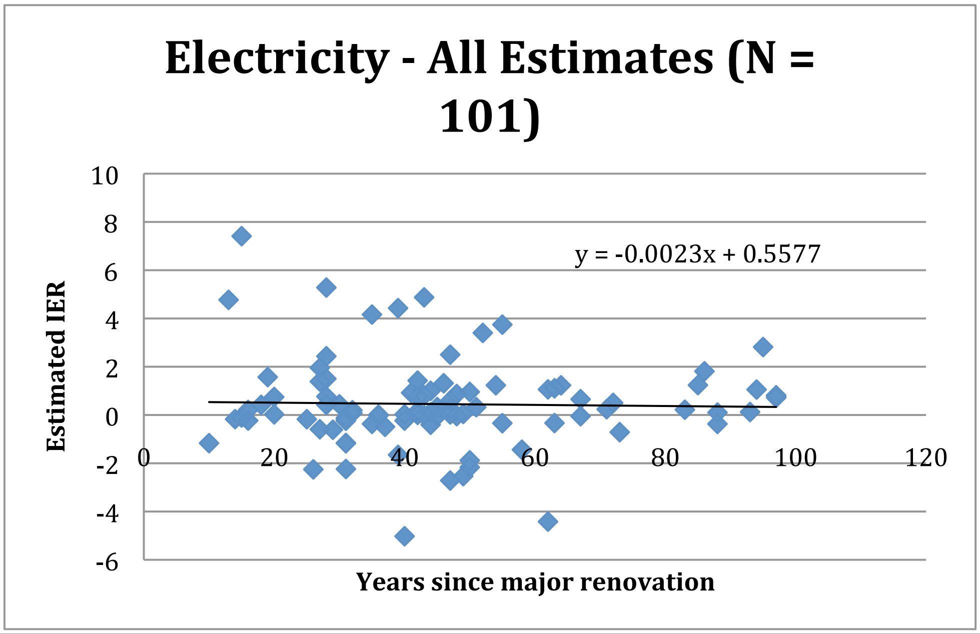
Estimating τ and E*: As described in the main text, we model the growth in building energy requirements using an exponential form:

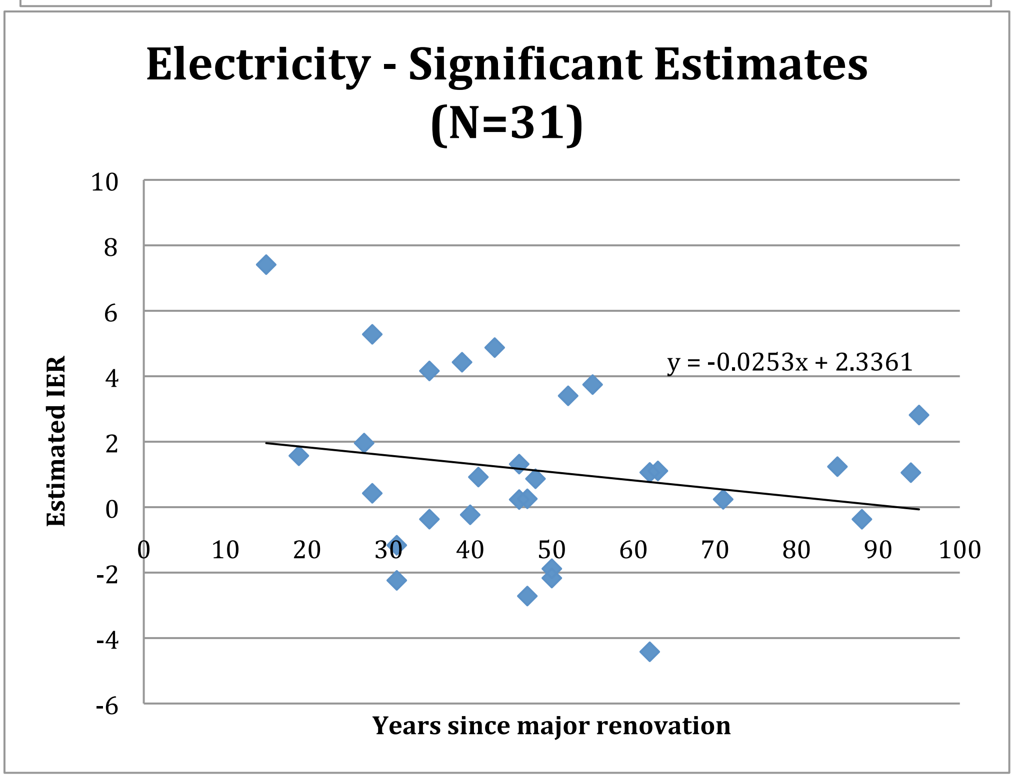
(6)

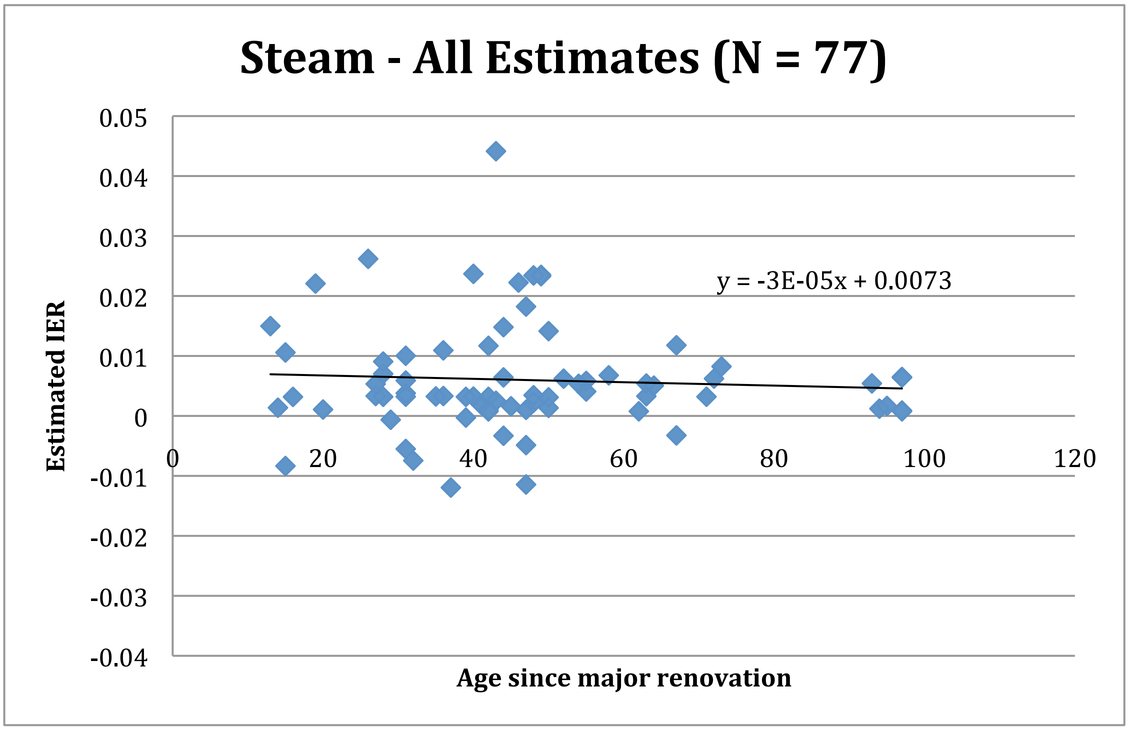
We use the data on building energy consumption to estimate the parameters τ and E*for each of the three energy types. To begin, we run individual regressions for each building with time again as an independent variable. We then plot the time trend estimate for each building against the age of that building (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:


Chilled Water - All Estimates (N = 60)
Estimated IER
9
8
7
6
5
4
3
2
1
0
-1
-2
-10.00
20.00
40.00
60.00
80.00
100.00
120.00
Age Since Major Renovation


Chilled Water - Statistically Significant Estimates (N = 15)
Estimated IER
9
8
7
6
5
4
3
2
1
0
-1
-2
0
20
40
60
80
100
120
Age Since Major Renovation


Electricity - All Estimates (N = 101)
y = -0.0023x + 0.5577
Estimated IER
Years since major renovation
10
8
6
4
2
0
-2
-4
-6
0
20
40
60
80
100
120


Electricity - Significant Estimates (N=31)
y = -0.0253x + 2.3361
Estimated IER
Years since major renovation
10
8
6
4
2
0
-2
-4
-6
0
10
20
30
40
50
60
70
80
90
100



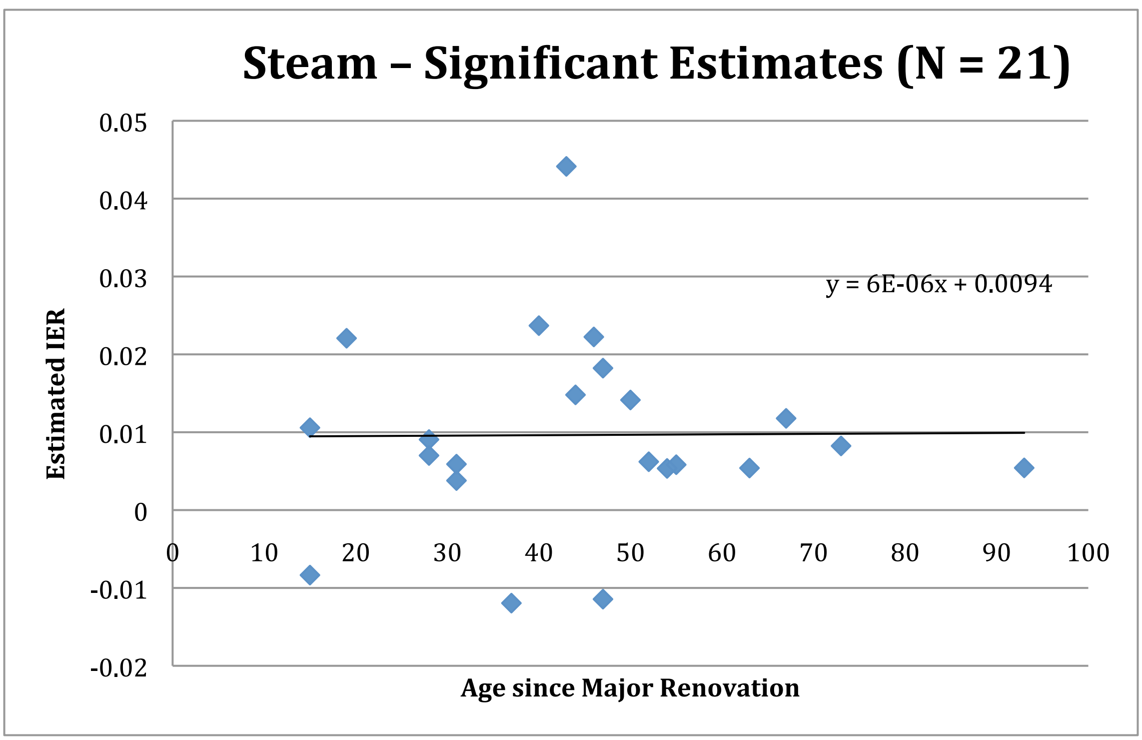


Figure 2: Plots of building age against regression estimates for the time trend (increase in energy requirements)

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

(7)

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

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

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

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 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(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.

	Chilled Water		Electricity		Steam	
Age Bucket	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).

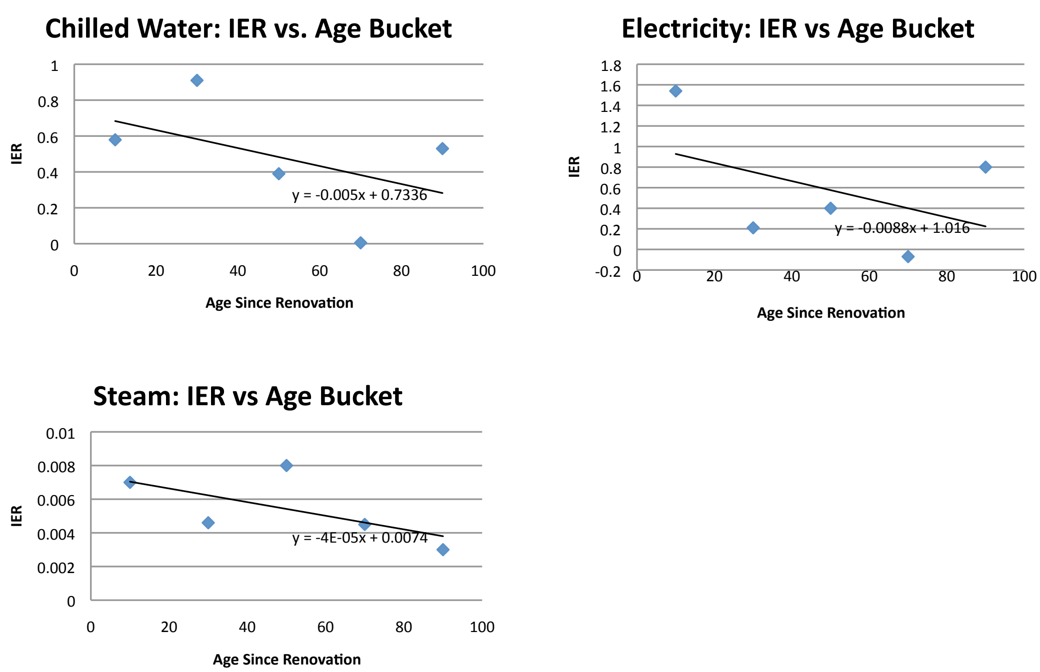


Figure 3: Plots of Building Age against the Estimated Increase in Energy Requirements (IER) for age buckets.

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.

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

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

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 Proactive Investment

The majority of model runs contain a proactive investment in maintenance. Below we describe exactly how that investment is implemented. 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 investments described in the main text are shown in figure 4:

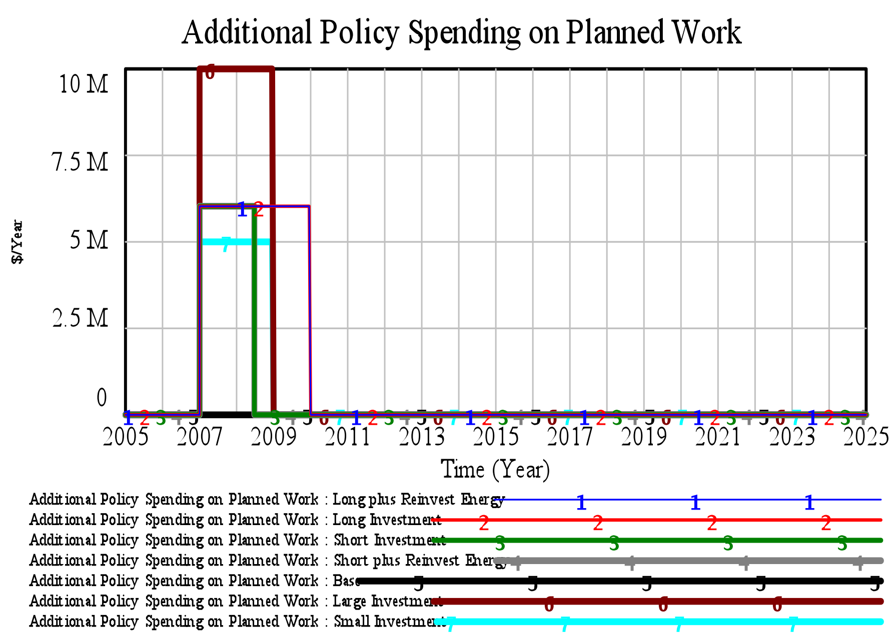


Figure 4: Time paths of investments for model runs shown in the paper

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

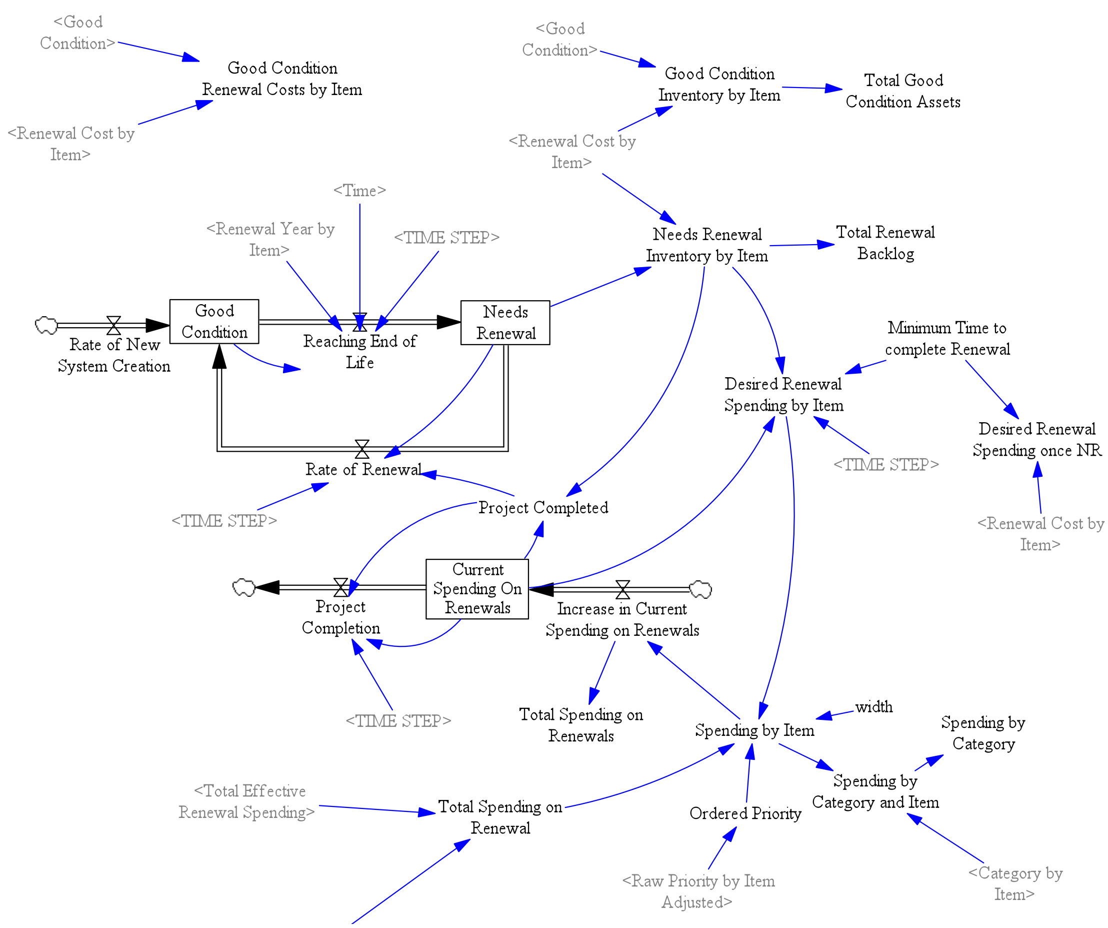


Figure 5: Model Diagram for the Building Renewal Sector

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

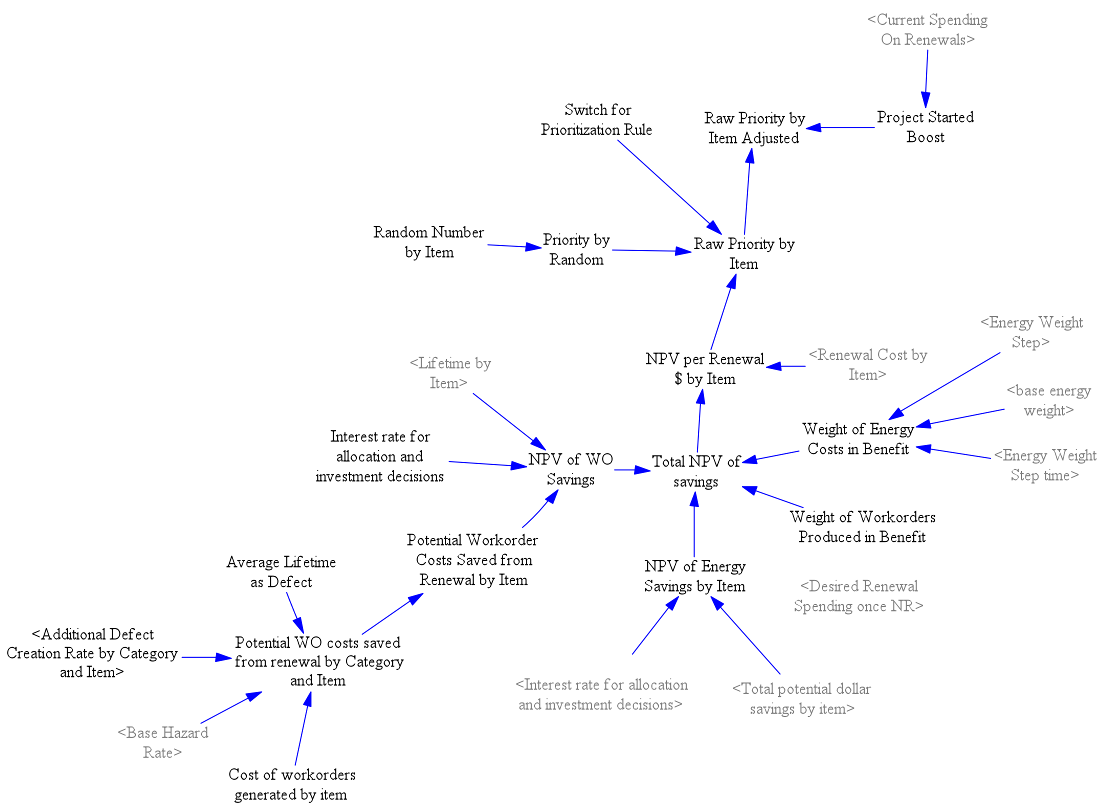


Figure 6: Model Diagram for the Prioritization of Renewal Items

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

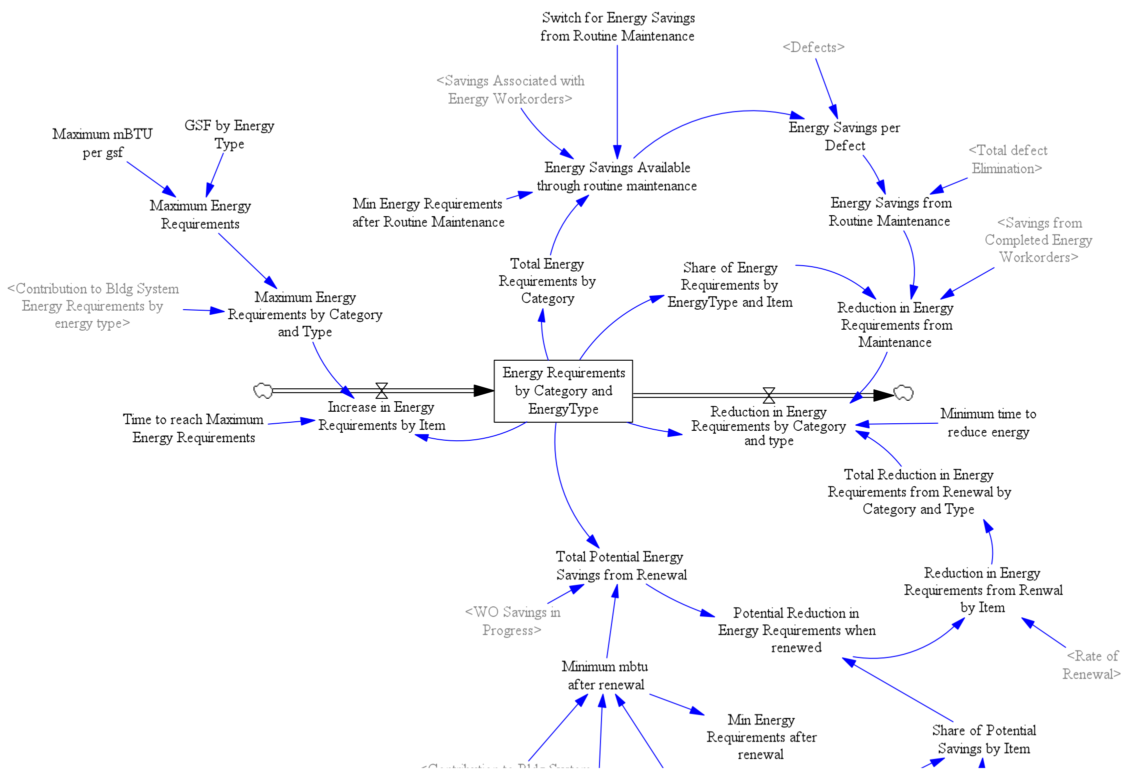


Figure 7: Model Diagram for Energy Requirements from Buildings

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

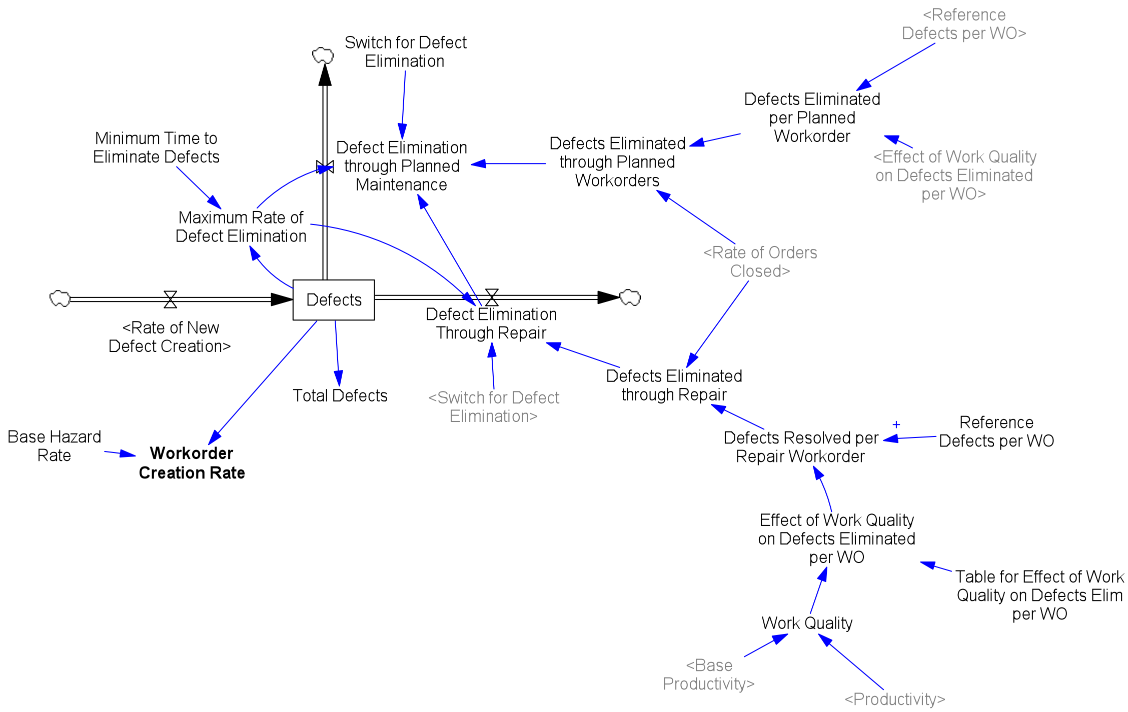


Figure 8: Model Diagram for Equipment Defects and Elimination

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

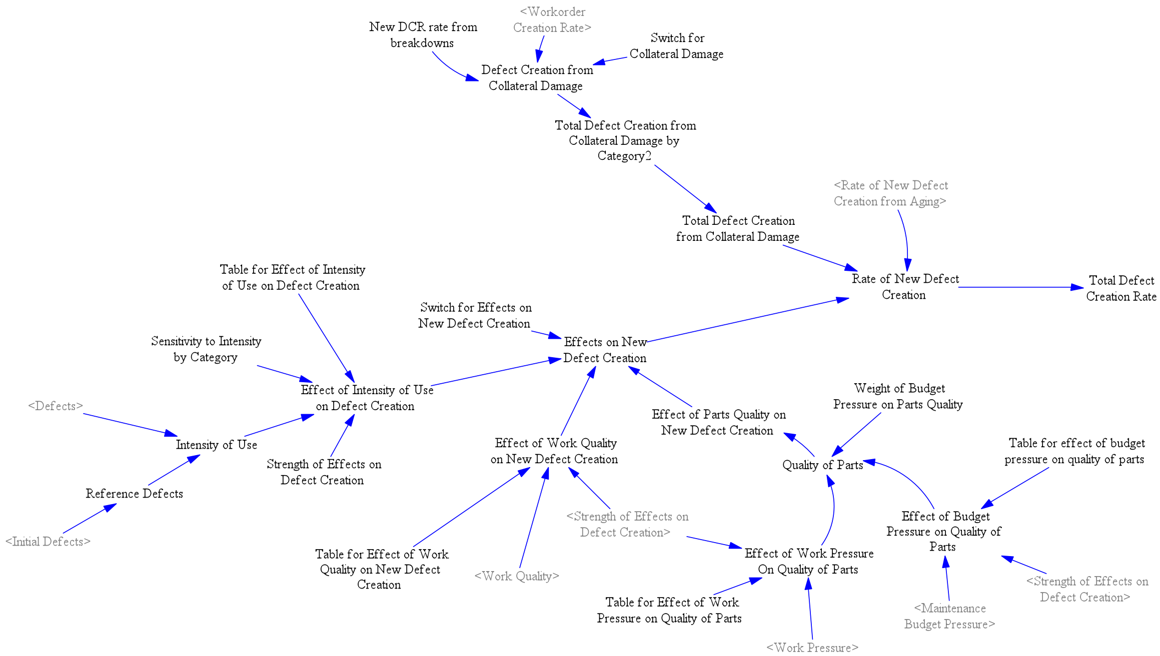
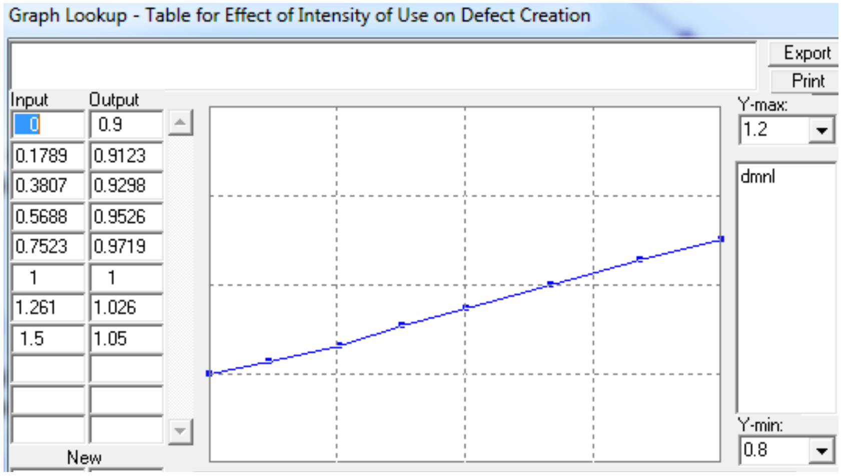


Figure 9: Model Diagram for Defect Creation

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

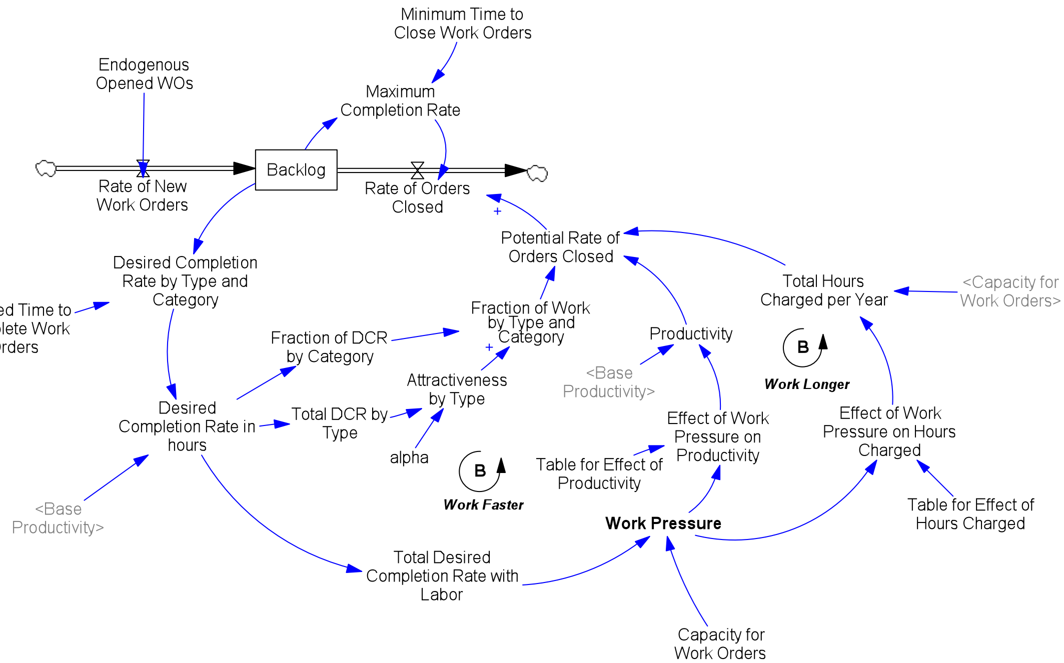


Figure 10: Model Diagram for Work Order Backlog and Completion

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

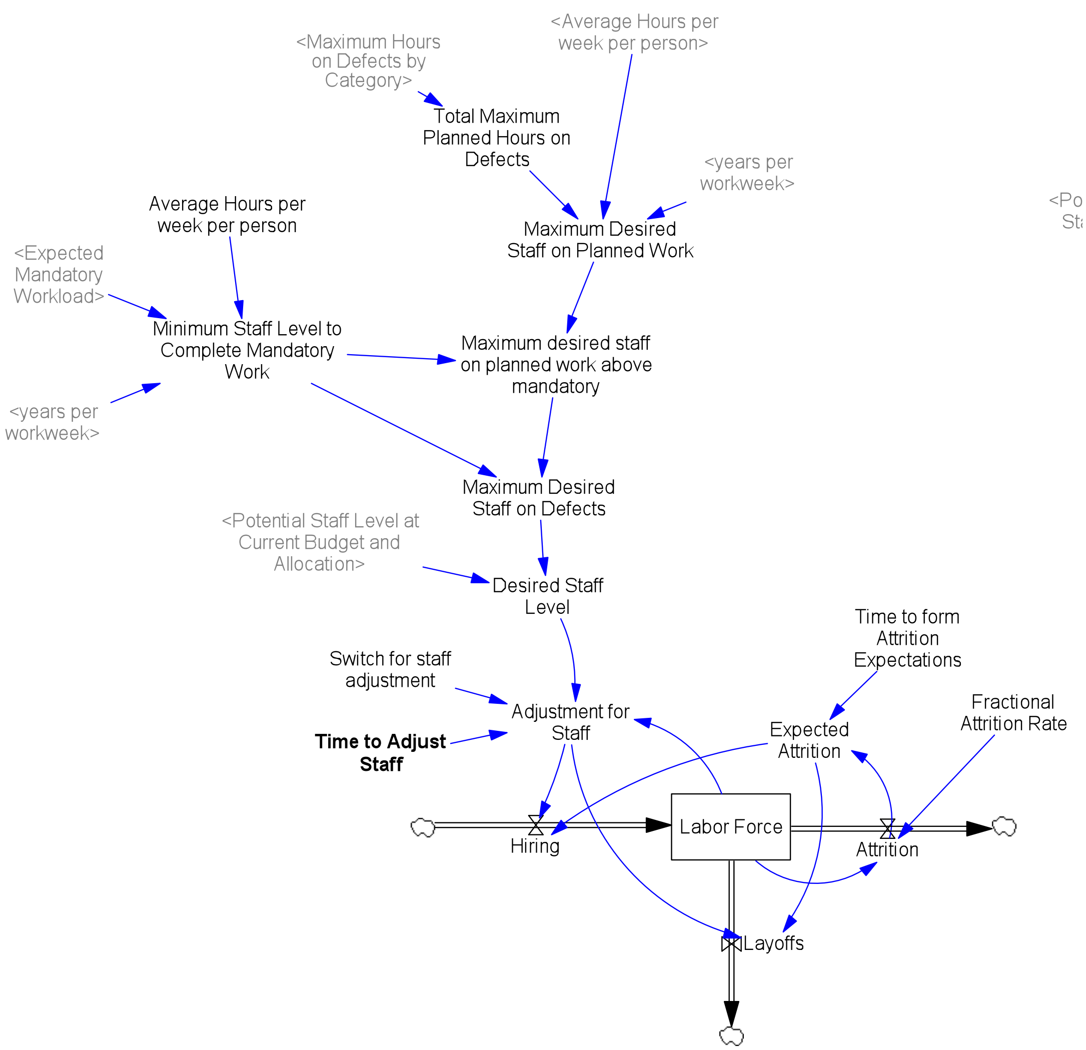


Figure 11: Model Diagram for Maintenance Staffing

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

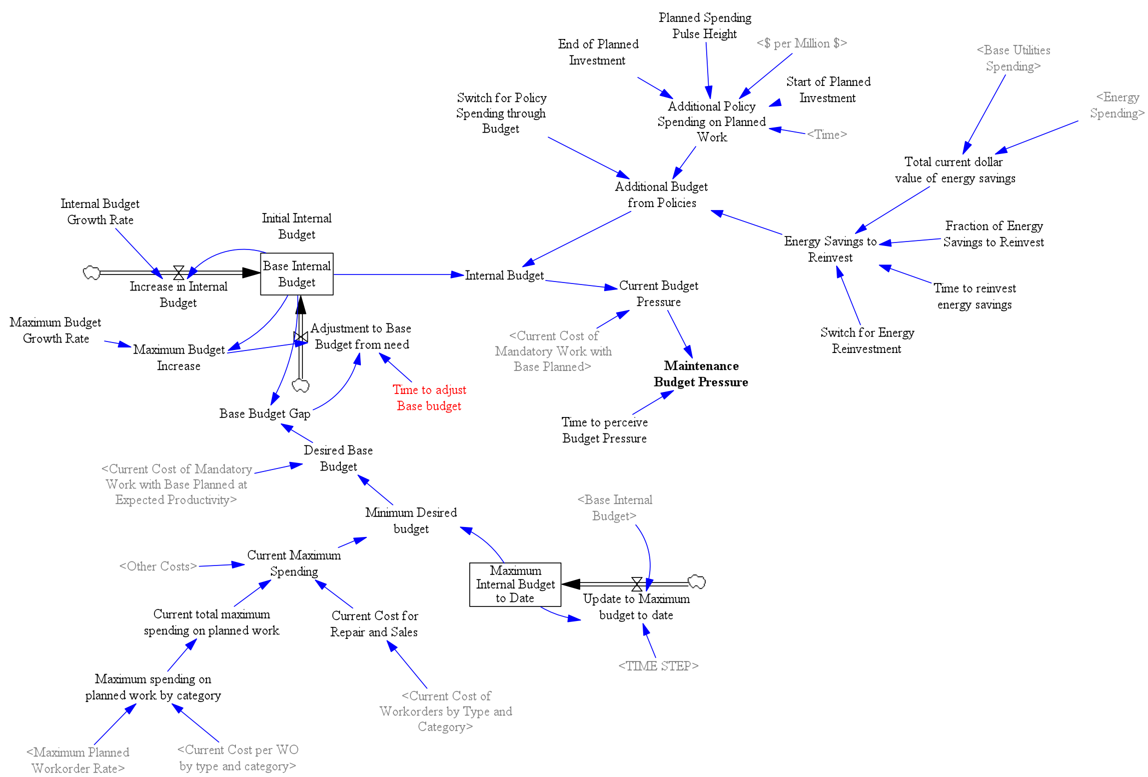


Figure 12: Model Diagram for the Maintenance Budget

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

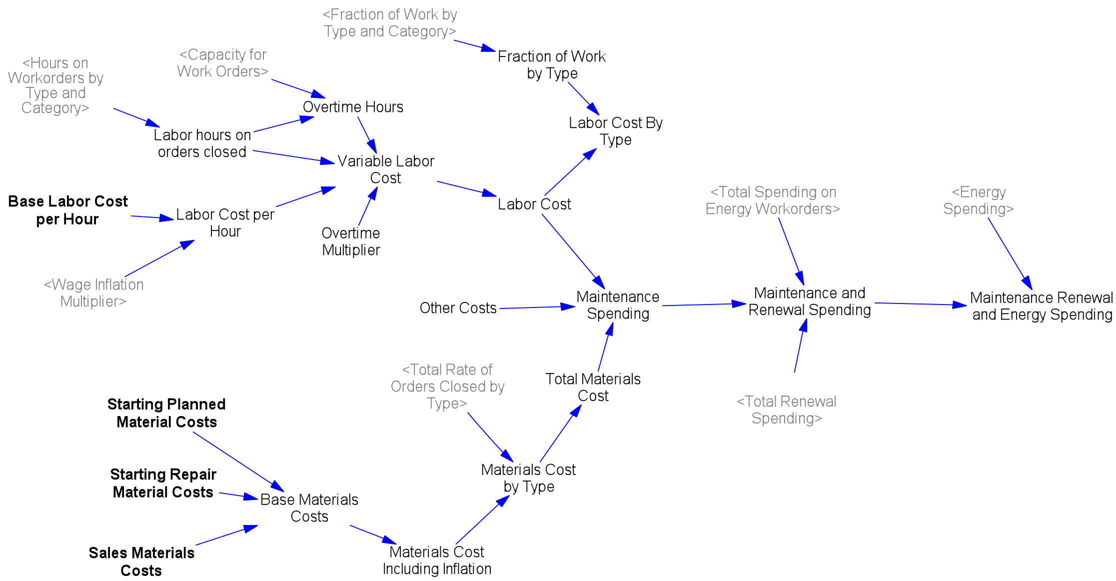


Figure 13: Model Diagram for Maintenance Spending

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

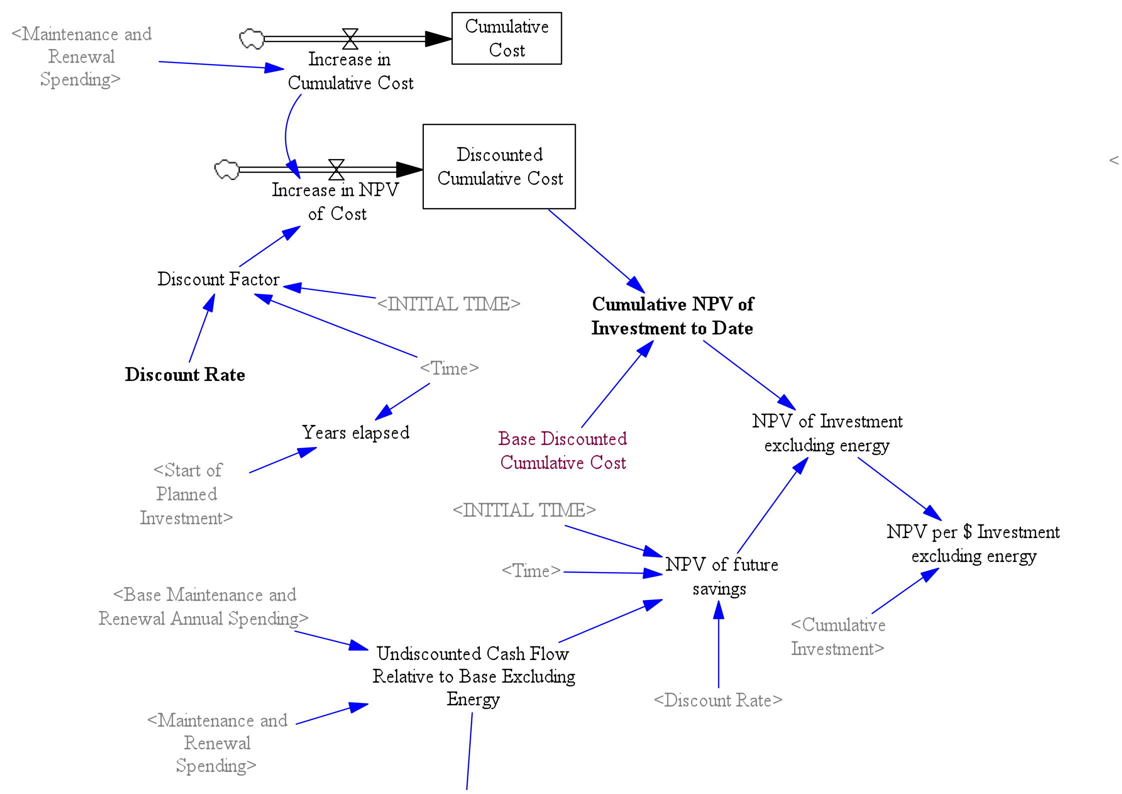


Figure 14: Model Diagram for the NPV Calculation

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.

The model is implemented in the Vensim simulation package (http://Vensim.com).

"$ per Million $"=1e+006Units: $/Million$
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=((Desired Staff Level-Labor Force)/Time to Adjust Staff)*Switch for staff adjustment
Units: ppl/Year

Adjustment to Base Budget from need=MIN(Maximum Budget Increase,Base Budget Gap/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*Total DCR by Type[Type]/365)
Units: dmnl

Attrition=Labor Force*Fractional Attrition Rate
Units: ppl/Year

Average Annual ROI Excluding Energy=zidz(Fractional Return,Years elapsed)
Units: 1/Year

Average Annual ROI including Energy=zidz(Fractional Return including energy,Years elapsed)
Units: 1/Year

Average Cost per WO=zidz(SUM(Average Cost per WO by Type[Type!]*Total Rate of Orders Closed by Type[Type!]),SUM(Total Rate of Orders Closed by Type[Type!]))
Units: $/workorder

Average Cost per WO by Category[Category]=zidz(SUM(Rate of Orders Closed[Type!,Category]*Current Cost per WO by type and category[Type!,Category]),Total Rate of Orders Closed by Category[Category])
Units: $/workorder

Average Cost per WO by Type[Type]=zidz(SUM(Rate of Orders Closed[Type,Category!]*Current Cost per WO by type and category[Type,Category!]),Total Rate of Orders Closed by Type[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

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

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: dmnl

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 CostsUnits: $/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 0.250 0 00 0 00.75 0.5 0.750 0.5 00 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: dmnl

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[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: dmnl [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

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 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

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

Discount Factor=exp(-Discount Rate*(Time-INITIAL TIME))
Units: dmnl

Discount Rate=0.05
Units: 1/Year

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: dmnl

Effect of Campus Condition on Reported Workorders per Year=Table for Effect of Perceived Campus Condition on Reporting(Perceived Campus Condition Indicator)
Units: dmnl

Effect of Campus Size on Defect Creation=GSF Relative to Initial*Switch for Growing Campus+1-Switch for Growing Campus
Units: dmnl

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: dmnl

Effect of Parts Quality on New Defect Creation=1/Quality of Parts
Units: dmnl

Effect of Service Expectations on Workorders per Defect=Table for Effect of Service on Opened WO per Defect(Relative Service Quality)
Units: dmnl

Effect of Work Pressure on Desired Completion Time=Table for Effect of Work Pressure on DCT(Work Pressure)
Units: dmnl

Effect of Work Pressure on Hours Charged=Table for Effect of Hours Charged(Work Pressure)
Units: dmnl 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: dmnl

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: dmnl

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: dmnl

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: dmnl

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: dmnl

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: dmnl

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 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: dmnl

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: dmnl

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: dmnl

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: dmnl

Fraction of DCR by Category[Type,Category]=zidz(Desired Completion Rate in hours[Type,Category],SUM(Desired Completion Rate in hours[Type,Category!]))
Units: dmnl

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: dmnl

Fraction of Defects that require renewal=0
Units: dmnl

Fraction of Energy Savings to Reinvest=0
Units: dmnl [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: dmnl

Fraction of Hours Repair=SUM(Fraction of Work by Type and Category[Repair,Category!])
Units: dmnl

Fraction of Hours Sales=SUM(Fraction of Work by Type and Category[Sales,Category!])
Units: dmnl

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: dmnl

Fraction of Maintenance Savings Achievable through routine maintenance[Category]
=0.2,0,0,0.5,0.1,0
Units: dmnl

Fraction of orders charged labor[Type]=1
Units: dmnl 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: dmnl

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: dmnl

Hiring=MAX(0,Adjustment for Staff+Expected Attrition)
Units: ppl/Year Hiring, measured in people per month. Assumed to be expected attrtion 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: dmnl

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

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: dmnl

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

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: dmnl

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

Initial Overtime Multiplier= INITIAL(1+(Initial Overtime Hours/Work Capacity))
Units: dmnl

Initial Planned Allocation[Category]= INITIAL(Indicated Discretionary PM Allocation[Category])
Units: dmnl

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: dmnl

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: dmnl

INITIAL TIME = 2005
Units: Year

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: dmnl

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: dmnl

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]=0Units: 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

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: dmnl

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

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=(Total Maximum Planned Hours on Defects)/Average Hours per week per person*years per workweek
Units: people

Maximum desired staff on planned work above mandatory=Maximum Desired Staff on Planned Work-Minimum Staff Level to Complete Mandatory Work
Units: people

Maximum Energy Requirements[EnergyType]=Maximum mBTU per gsf[EnergyType]*GSF by Energy Type[EnergyType]
Units: mBTU/Year

Maximum Energy Requirements by Category and Type[Category,EnergyType]=Maximum Energy Requirements[EnergyType]*Contribution to Bldg System Energy Requirements by energy type[Category,EnergyType]
Units: mBTU/Year

Maximum Hours on Defects by Category[Category]=zidz(Maximum Planned Workorder Rate[Category],Expected Productivity for planning[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]=(Defects[Category]/Minimum Time to Discover Defects Proactively)/Reference Defects per WO[Planned]
Units: workorders/Year

Maximum Rate of Defect Elimination[Category]=Defects[Category]/Minimum Time to Eliminate Defects
Units: Defects/Year

Maximum spending on planned work by category[Category]=Maximum Planned Workorder Rate[Category]*Current Cost per WO by type and category[Planned,Category]
Units: $/Year

Min Energy Requirements after renewal[Category]=SUM(Minimum mbtu after renewal[Category,EnergyType!])
Units: mBTU/Year

Min Energy Requirements after Routine Maintenance[Category]= INITIAL(Total Energy Requirements by Category[Category] - MAX(0,(Total Energy Requirements by Category[Category]))*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

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: dmnl

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
00 0 0 0 0 00 0.05 0.05 0 0 00 0
0.05 0.05 0 00 0 0 0.05 0.05 00 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: dmnl

NPV per $ investment including energy=zidz(NPV of Investment Including Energy Savings,Cumulative Investment)
Units: dmnl

NPV per Renewal $ by Item[Item]=zidz(Total NPV of savings[Item]-Renewal Cost by Item[Item],Renewal Cost by Item[Item])
Units: dmnl

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: dmnl 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=smoothi(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: dmnl

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]=0Units: 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]=Total Hours Charged per Year*Productivity[Type,Category]*Fraction of Work by Type and Category[Type,Category]
Units: workorders/Year

Potential Reduction in Energy Costs when Renewed[Item]=zidz(Renewal Cost by Item[Item],Simple Payback Time[Item])
Units: $/Year

Potential Reduction in Energy Requirements when renewed[Item,Category,EnergyType]=Total Potential Energy Savings from Renewal[Category,EnergyType]*Share of Potential Savings by Item[Item,Category]
Units: mBTU/Year

Potential Staff Level at Current Budget and Allocation=Possible Hours Funded at Current Budget and Allocation/(Average Hours per week per person
+Desired overtime hours per person for planning)*years per workweek
Units: people

Potential WO costs saved from renewal by Category and Item[Category,Item]=Additional Defect Creation Rate by Category and Item[Category,Item]*Base Hazard Rate[Category]*Cost of workorders generated by item[Item]*Average Lifetime as Defect[Category]
Units: $/Year

Potential Workorder Costs Saved from Renewal by Item[Item]=SUM(Potential WO costs saved from renewal by Category and Item[Category!,Item])

Units: $/Year

Preventive Defect Resolution Multiplier=1
Units: dmnl

Price of Energy by Type[EnergyType]=Energy Price by Year[EnergyType]
Units: $/mBTU

Price of other energy=20
Units: $/mBTU

Priority by Random[Item]=Random Number by Item[Item]
Units: dmnl

Proactive Workorders Completed=Total Rate of Orders Closed by Type[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: dmnl

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: dmnl

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: dmnl

Random Number by Item[Item]= INITIAL(RANDOM UNIFORM(0, 100 , 0))
Units: dmnl

Random Weight in Energy Savings[Item,Category]= INITIAL(RANDOM NORMAL(0 , 2 , 1 , Standard Deviation of Random Effect on Energy Weight, 1))
Units: dmnl

Rate of inflation for renewal costs=0
Units: dmnl

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

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

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

Rate of Orders Closed[Type,Category]=MIN(Potential Rate of Orders Closed[Type,Category],Maximum Completion Rate[Type,Category])

Units: workorders/Year

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: dmnl

Raw Priority by Item[Item]=IF THEN ELSE(Switch for Prioritization Rule=1,NPV per Renewal $ by Item[Item],Priority by Random[Item])
Units: dmnl

Raw Priority by Item Adjusted[Item]=(Raw Priority by Item[Item])+Project Started Boost[Item]
Units: dmnl

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

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

Sensitivity to Intensity by Category[Category]=0.1,0.1,1,1,0.5,0
Units: dmnl

Share of additional WOs by Category[Category]=zidz(Remaining potential WO by Category[Category],SUM(Remaining potential WO by Category[Category!]))
Units: dmnl

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: dmnl

Share of Potential Savings by Item[Item,Category]=zidz(Weighted Contribution to Energy Savings by Item[Item,Category],total weighted contribution[Category])
Units: dmnl

Simple Payback=IF THEN ELSE(Simple Return Excluding Energy>Size of Investment,1,0)
Units: dmnl

Simple Payback Including Energy Savings=IF THEN ELSE(Simple Return Including Energy>Size of Investment,1,0)
Units: dmnl

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: dmnl

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: dmnl

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

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: dmnl

Standard Deviation of Random Effect on Energy Weight=0.1
Units: dmnl

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: dmnl

Surplus Hours=MAX(0,Potential Planned Hours-Total Planned Hours on Defects)
Units: hours/Year

Switch for Additional External Spending=1
Units: dmnl [0,1,1]

Switch for Calculated Defect Creation Rate=0
Units: dmnl [0,1,1]

Switch for Collateral Damage=1
Units: dmnl

Switch for constant inflow=0
Units: dmnl [0,1,1]

Switch for Constant Sales WO Rate=0
Units: dmnl [0,1,1]

Switch for Defect Elimination=1
Units: dmnl [0,1,1]

Switch for Effects on New Defect Creation=1
Units: dmnl

Switch for Endogenous DCT=1
Units: dmnl

Switch for Energy Reinvestment=1
Units: dmnl [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]

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: dmnl

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: dmnl

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: dmnl

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: dmnl

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: dmnl

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: dmnl

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: dmnl

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: dmnl

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: dmnl

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: dmnl

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

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

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 to form Attrition Expectations=0.2
Units: years

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

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: dmnl

WO cost Std Deviation Factor=0.4
Units: dmnl

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: dmnl

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

Years to calculate inflation=(Time-Base Year for Inflation)*One over Year
Units: dmnl