Playing the Maintenance Game: How Mental Models Drive Organizational Decisions

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Nature has equipped organisms with the ability to regenerate or repair themselves when damaged. If I cut myself, healing takes over without need of conscious direction. If I am hurt badly enough, the body's needs will make themselves known and tend to preempt voluntary activities. In this way, a balance between short-term interests (e.g., continuing to work or play) and long-term interests (staying healthy) is established on terms that derive from an evolutionary logic. Similarly, nature strikes a balance between parts and whole, for example, by diverting blood supply in cold weather to preserve the critical internal organs, although risking frostbite to the extremities.

Business decisions about short-term and long-term interests, and local and global interests, have no evolutionary logic or built-in process to rely upon. Instead, these decisions are based on the limited understandings, rules of thumb, and traditional practices of organizational actors (March & Shapira, 1982). Research suggests that undue attention or decision weight may be given to the short term because the future is ambiguous or discounted (March, 1978; Loewenstein & Prelec, 1992). It is difficult for actors to understand the global and delayed consequences of local decisions and immediate actions (Senge & Sterman, 1989; Sterman, 1989a,b), and this is particularly difficult in tightly-coupled (Perrow, 1984) or highly-interdependent organizations.

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[1] The writing of this paper was supported by the MIT International Program on Enhanced Nuclear Power Plant Safety, a research program of the MIT Energy Laboratory sponsored by an international group of nuclear power utilities and relevant institutions. John Sterman acknowledges the financial support of the MIT Organizational Learning Center. This paper will appear in R. N. Stern & J. J. Halpern (eds.), Debating rationality: Nonrational aspects of organizational decision making. Ithaca, NY: Cornell University ILR Press.

In this paper, we will present some evidence for the failure to give due consideration to preventive maintenance in organizational decisions taken by two companies in two different industries. In the short run, a plant can always cut preventive maintenance; the problems emerge later because preventive maintenance is an investment in the future. We suspect that the reasons for these decisions have some similarity. Further, we think that sparse allocation of resources to maintenance is not a rational strategy <u>for the organization as a whole</u> -- it is a strategy that gets organizations deeper in trouble. Indeed, <u>once recognized</u>, organization members reject this pattern of behavior but have great difficulty overcoming it. There are some important psychological and organizational reasons why insufficient preventive maintenance may be <u>locally</u> rational in the sense of being in the best short-term interests of individuals who have limited understanding and/or concern for the longer-term and more global consequences.

As illustrated in the two case studies, underlying these maintenance issues are assumptions and understandings that we designate as the "mental models" of the organization participants. The term "mental models" is used in many ways (Gentner & Stevens, 1983; Jungermann & Thuring, 1988; Morecroft & Sterman, 1994; Rasmussen, 1979; Rouse & Morris, 1986; Senge 1990) referring to the causal understandings people have about how a system works, the scripts they use to guide conduct and behave appropriately in various situations, and the deeply embedded cultural assumptions that condition behavior, attitudes, and perception. We use mental models to refer to beliefs and understandings at all levels of analysis: individuals "have" mental models, but portions of these mental models are shared across workgroups and professional specialties, and embedded in organizational or national culture. We argue that the local rationality and global irrationality of individual action arises because actors' mental models are simplifications that do not capture the fullness of complex, dynamic systems (Forrester, 1961; Simon, 1979).

We also describe the successful efforts of one company to improve organizational performance by focussing on new ways of learning about the dynamic interdependencies around the maintenance function. As we explore the way in which these decisions were made, we suggest ways that organizations can improve their decision making around maintenance and, indeed, around many important issues, by recognizing that decisions are based on incomplete, partially-shared mental models whose coherence and comprehensiveness can be enriched through learning.

Maintenance at Du Pont[2]

Background

Du Pont, with 1991 sales of more than $38 billion and after-tax profits of $1.4 billion, is by far the largest U.S. chemical manufacturer. Most of its chemical products are manufactured in continuous-processing plants, which theoretically run 24 hours per day, seven days per week, without shutting down or re-fitting for new batches of product. The goal is to maximize uptime (when the time the plant is in full operation); the shut-down and startup processes stress the plant and equipment, are energy-intensive, require operators and mechanics to work overtime under pressure, and could prevent Du Pont from delivering product to a customer on time.

Despite efforts to maximize uptime, the average chemical plant operates only about 83-95% of the time, depending on the particular type of plant. The remainder is downtime caused by critical equipment being serviced or awaiting service. The mean time between failures (MTBF) of equipment and the speed and quality of maintenance operations are therefore critical determinants of uptime and plant profitability. Maintenance expenses account for 15-40% of production costs, depending on the type of manufacturing process. The amount of money Du Pont spent company-wide on maintenance in 1991 was roughly equal to its net income.

The Problem

[2] This description is taken from Sterman, et al. (1992). John Sterman acknowledges the assistance of Ellen Banaghan, Mark Paich, and Elizabeth Gorman; Winston Ledet, Mark Downing, Tony Cordella, and others at Du Pont are particularly acknowledged for generously sharing their efforts, data, and hospitality. This work was supported in part by the Organizational Learning Center, MIT Sloan School of Management.

In 1990 Du Pont undertook a competitive benchmarking study to measure the effectiveness of its maintenance programs relative to the top performers in the worldwide chemicals industry. The benchmarking study revealed an apparent paradox: Du Pont spent more on maintenance than industry leaders but got less for it (see Table 1). Du Pont had the highest number of maintenance employees per dollar of plant value, yet their mechanics worked more overtime. Spare parts inventories were excessive yet the plants relied heavily on costly expedited procurement of critical components. Most disturbing, though, Du Pont's direct maintenance costs per dollar of plant value were 15% higher than the average of the industry leaders, yet availability of critical equipment and overall plant uptime lagged far behind.

Insert Table 1

As in many industries today, chemicals producers are under strong pressure to reduce costs and improve productivity. In the past twenty years, the three worst recessions since the Great Depression caused widespread excess capacity. New competitors from the Pacific rim and the oil-rich nations of the Middle East have entered the market. Two severe energy crises wreaked havoc with input and operating costs. Environmental concerns and regulations continue to grow. Du Pont Chemicals responded to the intense cost competition with a series of cost-reduction initiatives over the past 10 years; more recently, Du Pont (corporate) has undertaken a $1 billion cost reduction effort throughout its manufacturing divisions.

Maintenance, like other manufacturing functions, has come under pressure to improve its cost effectiveness. When maintenance departments are asked to cut expenses, nearly all of the cut has to come from activities such as planning and preventive maintenance rather than corrective maintenance, because breakdowns in critical equipment must be fixed. At the same time, cost-cutting often results in other actions (e.g., postponing replacement of older, less reliable equipment or eliminating backup capacity) which increase the load on maintenance departments. With resources for preventive maintenance diminishing and maintenance needs increasing, a plant's equipment begins to break down more often. Maintenance managers must then shift more of their limited parts stocks and mechanics from preventive maintenance to corrective maintenance. Growing volumes of work orders for corrective maintenance further reduce resources available for preventive maintenance, leading to still more breakdowns, in a vicious spiral of self-reinforcing feedback.

Some Du Pont employees, observing this process unfold over several decades, had concluded that Du Pont had developed a culture of reactive maintenance. Unreliable equipment and frequent breakdowns had become an accepted occurrence. Organizational norms and routines for writing up work orders, scheduling maintenance effort and ordering parts had come to reflect a world of frequent breakdowns. Mechanics spent most of their time "fighting fires"; those mechanics who were scheduled for predictive or preventive work were routinely pulled off those jobs to do corrective work. Mechanics knew they could work overtime on a regular basis and considered overtime pay a part of their regular income. The "knowledge" that equipment was unreliable had even led to installation of backup pumps in many sites, embedding the low-reliability culture in the physical layout and capital costs of the plants.

<u>Early Change Efforts Fail</u>

The results of the benchmarking study served as "marching orders" for the Corporate Maintenance Leadership Team (CMLT), a group formed in 1988 with the objective of using effective maintenance operations to keep chemical plants running at near full capacity at a reasonable cost. The CMLT had created eight separate Key Pursuit Field Teams (Planning and Scheduling, Predictive/Preventive Maintenance, Materials Management, Contracted Maintenance, Competitive Position Assessment, Human Resource Development, Maintenance Technology, and Maintenance Leadership) to identify strategies and products that could reduce maintenance costs, and "sell" these ideas to the plant operations managers. Based on the teams' recommendations, many plants began a variety of initiatives to reduce maintenance costs. But while some of the initiatives reduced maintenance costs and improved uptime in the short term, many gains were short-lived, and management began to question the value of these initiatives.

Meanwhile, the Competitive Position Assessment (CPA) team was discovering that minimizing costs could backfire. A lack of resources in one area of the plant could put undue stress on other areas, causing additional expenses which outweighed the initial cost savings. For instance, cost-cutting reductions in spare parts supply handlers could easily <u>raise</u> costs: preventive maintenance might be delayed while the remaining supply personnel expedited emergency work orders, further delaying preventive work and causing increased breakdowns and additional costly expediting of replacement parts orders.

<u>Deficient Mental Models</u>

The CPA field team felt that while the benchmarking study provided an excellent assessment of Du Pont's relative functional performance, it did not indicate what actions needed to be taken to improve maintenance effectiveness. They felt that focusing on the correlates of maintenance success revealed little about the forces that produced and perpetuated low maintenance productivity. Furthermore, the CMLT's approach to maintenance had previously been to focus on minimizing costs. The unquestioned underlying assumption was that minimizing maintenance costs would help minimize overall manufacturing costs, ie., maintenance costs could be viewed as loosely coupled or independent from other functions.

The CPA team intuitively felt that maintenance was tightly linked to other functions through complex feedback relationships. Although some relationships were clear (e.g., more mechanics mean faster maintenance response time), considering the simultaneous effects of multiple variables quickly became too complex. Similarly, it was difficult to understand what would happen under alternative maintenance scenarios if the plant were subject to unanticipated production demands or cost pressures.

Maintenance at a Nuclear Power Plant[3]

Background

Peninsula Haven nuclear power facility is operated by the People's Power Company. Like chemical process plants, nuclear plants are run continuously to generate electricity (other sources of electricity are easier to turn on and off and are used for the variable part of electricity demand). Nearly all the large-scale repairs and testing are performed during scheduled outages that take one to four months and occur less than once a year. Unlike chemical plants, nuclear plants do not directly compete with one another, but rather operate in the public interest with service areas and rate structures determined by public authorities. Further, the potential for catastrophic releases of radiation has led to intense public scrutiny and regulations that enforce a much higher level of attention to safety than in the chemical industry.

There are two separate nuclear power plants on site at Peninsula Haven: Colonial, which has operated for over a dozen years, and the newer Alexander Grant. The two plants have design differences that prevent moving licensed operating staff between units: for example, instrumentation and control is analog at one unit and digital at the other, and control rods come down at one unit and go up at the other. They also have had dramatically different performance records.

The Problem

When Colonial first started to produce power, and Alexander Grant was in the planning and construction stages, Peninsula Haven still had a "fossil mentality." At fossil (coal and oil) plants, you "run a boiler and shovel coal into it till it falls apart." If a boiler was not maintained

[3] This summary is based upon Marcus (1992). The names of the utility and the power plants have been disguised. Material in quotation marks is drawn from interviews or documents. This research was part of the MIT International Program for Enhanced Nuclear Power Plant Safety.

properly, it could be overhauled easily. Operators had considerable freedom to do what they wanted to keep a plant running. Protective systems did not exist, radiation was not a concern, and there were fewer codes and standards than at a nuclear plant. Employees operated on a very short-time frame, a "month-by-month" basis. Thus, work practices developed around the reactive maintenance culture common to the fossil fuel industry.

An important safety incident took place in the mid-1980s when Colonial failed to shut down automatically in response to a problem; fortunately, an operator noticed the indicators calling for shutdown and initiated a manual shutdown. Responding to demands by the U.S. Nuclear Regulatory Commission (NRC) for an investigation, the utility found that a fundamental component had not been "prudently maintained." The NRC then brought in a team of investigators who unearthed numerous problems in how Colonial was "glued together" as an organization.

Change Efforts Fail

In response to a detailed action plan mandated by the NRC and extensive recommendations by outside consultants hired by the utility, People's Power made many changes in their nuclear power operation and management. A major focus was on fixing procedures that did not work. They developed a procedure for how to write a procedure. They continued programs to create common procedures for the different units, modelling the standardization program after that of another large utility which had tried to establish common procedures for its plants.

Following recommendations to appoint an outsider as vice president of nuclear power generation, the utility hired a new vice president with a nuclear Navy background. His standards were "very high," and he wanted to make People's Power "among the best operating utilities in the world in 5 years." He made a "major, visible attack" on the traditional system of promoting anyone who simply "went along" and kept out of trouble. He introduced management by objectives, with indicators against which to judge key personnel. This system made plant management "more formal" and forced people to think "more" in terms of the "long term." He managed by "walking around" and expected other managers to follow his example -- to be "out in the field" and close to their people. He brought in outside consultants who helped set up new hiring and discipline programs.

During this time, the CEO initiated an exhaustive productivity study to decrease costs at Peninsula Haven. Many cuts were made, including at Colonial, although Alexander Grant "came out with additional resources."

The results of these changes were somewhat mixed. The new vice president's main accomplishment was starting up Alexander Grant on-time and on-budget. He changed the mindset from construction to operations. He created the departments and established a very "strong team," although he was less successful at bringing Colonial "up to speed." Judged just by quantitative indicators, Colonial was improving, but he "did not build an infrastructure to survive him" after he left. The effort at creating consistent procedures succeeded in radiation chemistry but failed elsewhere (e.g., operations) because the two units were so different and a procedural compliance emphasis was resisted by those with fossil backgrounds.

Change efforts continued after the vice president was replaced by his understudy. New plant managers were appointed, and both were sent to the Harvard Business School to take the senior managers' course. Key people were moved from Alexander Grant to Colonial. The plant manager at Colonial had been an operations manager at Alexander Grant; several other functional managers had worked at Alexander Grant. Emphasis was placed on the mission and on training in "reaching the vision" that included material on interpersonal skills, understanding people, and employee behavior. Revitalization was an "integrated program of procedure improvement and material upgrade." So far the emphasis had been on "general equipment and housekeeping," but part of the program was to make procedures "more correct" and have them take into account "human factors."

To instill a culture of procedural compliance at Colonial, management had to do more careful "monitoring" and had to be certain that employees were being held "accountable." Management should be emphasizing "quality," "assigning responsibility," and "empowering people." Its style should be "more brutal." Employees who did not adhere to procedures had to be "punished" to get a "commitment from them to do the right thing in the future." Yet, given the plants' "demanding schedule," employees had to be intrinsically motivated to get their jobs done in a "quality" way. While employees felt that they could not act without procedures, there were not enough procedures "to cover all bases." The procedure would say "push the stop button," and after pushing it the operator would feel that he had completed his task -- even if the pump did not stop. Because of "rote" learning of procedures, employees did not have a "sense of connection" or understanding of the "system" as-a-whole.

Another "piece" of the revitalization program was backlog reduction. The maintenance backlog at Colonial was "above the norm for the industry," and there was "some money beyond the base budget" to bring in contractors to "clean up" the backlog. However, it was hard to reduce the maintenance backlog when so many spare part suppliers had gone out of business, despite efforts to keep a large inventory. Although the corrective maintenance backlog at both Colonial and Alexander Grant were similar to the average of the nuclear industry, overdue preventive maintenance was much higher at Colonial than at Alexander Grant, which was near the industry average (see Table 2). Unless this preventive maintenance was unnecessary, such deferred maintenance would lead eventually to failures that would increase the corrective maintenance load over time.

Insert Table 2

The revitalization program also called for a systematic review of maintenance activities to determine where the "biggest bang for the buck" could be achieved in capital improvements. Perhaps if equipment was replaced rather than repaired, it would reduce the amount of maintenance that had to be done. The capital improvement program, though, was not in "full swing" yet. When Peninsula Haven decided to replace obsolete systems, the engineering group had to be cautious about design changes and would work slowly. In any case, given demanding outage schedules, it would be hard to implement change rapidly.

Despite continued efforts to improve and numerous signs of improvement, Colonial did not achieve a sense of self-confidence. Colonial never seemed to be able to solve its problems before "even bigger and more demanding" problems came along and distracted it. Based on its troubled history, the NRC and INPO (the Institute for Nuclear Power Operators, an industry-wide support organization) continued to "senselessly beat" it, which hurt "morale" and discouraged people from doing better. The situation deteriorated, with "name calling" and the staff losing "incentive, impetus, and enthusiasm." Colonial needed 2 to 3 years of a "good, solid run" and "constant improvement" to change the "psyche" of "losing."

Colonial did have a "great" year: it achieved a capacity factor above 70 percent, it had no "personnel induced" forced shutdowns and was in INPO's best quartile for fewest reactor forced shutdowns, and the number of personnel errors was "trending downward." The utility was "very happy" with its performance, and considered that further improvement would be facilitated if Colonial would gain more confidence and stop being perceived as a "loser."

A Severe Incident

A severe incident developed very quickly after many months of a good run. During a routine monthly test, the failure of three separate protection valves permitted severe damage to equipment. Safety systems were activated and functioned as expected. These valves were found to have been "mechanically bound" because of "accumulated debris." The valve failures had not been detected in part because the vendor did not require preventive maintenance of these valves, and industry focus was on safety systems that protect the reactor rather than the remainder of the plant.

However, personnel at Colonial should have known of the potential for this type of failure. Three prior events had occurred at other plants which involved similar protective equipment "not functioning as designed." These events had "not been recognized or addressed." Colonial also had a prior event in which the valves had functioned "erratically." Peninsula Haven had committed to replace the valves "during the next outage of sufficient duration," and preventive maintenance was to be initiated. Colonial had a mini-outage for maintenance purposes but the "decision was made to defer the valve replacement" to an upcoming refueling outage. During a reactor startup, the valves had been tested, and the test had indicated a "failure" of the protection system. However, the failure was attributed to "procedural problems," and "control room personnel decided to continue the startup without further probing or inquiry."

In retrospect, it was "easy to say so now" that judgment was poor, but at the time what was done made sense. During the Colonial mini-outage, employees completed "in excess of 1200 work requests to improve the safety and reliability of the plant." The outage manager had to look at "thousands of things" that could have been done. The reason these valves were not in "category #1" was that they were tested during the prior startup and would be tested again during this start-up. The work order did not provide for a complete assessment of downside risks. Plants had these events in the past without serious damage. The commitment was to fix the valves during the next available outage of "sufficient duration." So the decision makers "leaned on hope and were disappointed."

Nonetheless, policies for preventive maintenance had not developed rapidly enough. The previous vice president had started the reliability-centered maintenance program and was committed to it; but after he left, the budget was cut, programs were reallocated, and preventive maintenance declined in importance. It was difficult to gather data on past failures and re-occurring maintenance problems and subject them to assessment. External industry data were hard to analyze: INPO alone had 9 different programs, NRC 2, the vendors 7, and there were 3 internal programs. The typical Colonial response to information about industry experience was that its procedures were adequate; it "missed the generic implications" and refused to acknowledge the problems. Alexander Grant, in contrast, gave very specific, direct responses to the questions raised by industry information.

Mental Models about Maintenance

The Du Pont and Peninsula Haven experiences suggest that good companies can get in trouble when their attention to maintenance (especially preventive maintenance) slips. In our research project examining safety issues in nuclear power plant management and organization (Carroll, Perin, & Marcus, 1992), we have observed that the maintenance function is often given too little attention. Further, this is not just another item with which management must contend; it is unusually hard to fix this problem because the causes are subtle and systemic. We believe that difficulties in managing maintenance arise, in part, from limitations in mental models, revealed in several observations about the Du Pont and Peninsula Haven maintenance stories.

First, managers in general and perhaps U.S. managers with engineering backgrounds in particular, tend to think in terms of parts rather than wholes. They see a plant as a set of functional areas or parts in a machine; improvement programs start by creating separate task forces (such as the 8 teams formed at Du Pont) that partition activities into components that are presumed to be separable. Although this decomposition strategy can be very effective, if the issues lie at the interfaces or interstices of highly interdependent components, then this strategy is unlikely to succeed. For example, the strongly-held separation of nuclear safety from worker safety and the associated decomposition of the plant into reactor and balance of plant can mask issues that cut across both. This is part of the argument made by Perrow (1984), who considers nuclear power plants to be "tightly coupled" (ie., highly interdependent) relative to other manufacturing plants (in general, continuous processing plants including chemical plants are highly interdependent). The tendency to decompose tightly coupled systems is further reinforced by training and employment contracts that limit employees to specific jobs without cross-training, job rotation, or understanding of how their work relates to the big picture.

Second, people have difficulty integrating events and relationships over time and, as a result, mental models tend to misperceive feedback and focus attention on the wrong things (Sterman, 1989a, b, 1994). Mental models often emphasize a succession of discrete events rather than underlying patterns of behavior (Axelrod, 1976; Forrester, 1971; Richardson, 1991) and ignore or gloss over dynamic elements including feedback loops, time delays, accumulations (stocks and flows) and nonlinearities (Axelrod, 1976; Diehl & Sterman, 1995; Funke, 1991; Sterman 1989a, b). The result is a focus on short-term and local rather than long-term and global issues. For example, at Du Pont neither management nor shopfloor employees really understood the linkages between lack of planners and mechanics and the chronic corrective maintenance and high level of downtime. At Colonial, upgrading of procedures, management, housekeeping, training in achieving the vision, and so forth were done as separate improvements; no overall understanding directed attention at the deficiency in preventive maintenance and its potential impact.

The tendency to focus on short-term and local issues can be amplified by organizational factors. In the U.S. in particular, the reward structure in industry emphasizes annual or quarterly performance reviews and a person is judged by what they have done lately. It is partly that people expect to change jobs and even companies during their careers, so that their activities have to create performances that can be associated with them in a timely way. The result, however, is lessened attention to and understanding of longer-term issues and a lack of investment in activities that take time to produce results. The time horizon problem is exemplified in the cost-cutting pressures at

Du Pont and Peninsula Haven that required each manager to look for redundant and less-productive activities to trim. Preventive maintenance is a prototypical activity that seems low priority in the face of immediate demands to keep the machines running at lower cost, and the ultimate effects of deferred maintenance can be denied, ignored, or blamed on others.

Third, it is natural to focus attention on the people who seem responsible for the plant -- the operators (and, in the airline industry, the pilots). Operators are the ones with their fingers on the switches. They must take action if anything goes wrong, so they are the last line of defense. Their errors are highly evident and dramatic (such as at Chernobyl, when the operators turned off all safety systems in order to test the reactor's behavior). For decades, they were the focus of human factors initiatives and expensive simulator training (Rasmussen & Batstone, 1991). Maintenance as a concept is not as vivid within the "vision" of the organization: it is seen as a support rather than core activity, part of the costs rather than the revenues, blue-collar rather than professional, and one can imagine power production without even thinking about maintenance. Only recently has attention shifted away from operations to other functional areas of the plant (e.g., maintenance), the desirability of a safety culture (IAEA, 1991), and the management and organization of the plant as a whole.

Fourth, when management and organization are implicated in plant deficiencies and difficulties in the change process, the natural assumption is to look to leadership as the source of the problem and the source of solutions. Just as some baseball teams fire the manager after a bad season, nuclear power plants sometimes change top management (vice president of nuclear) as a strategy for changing a losing season. For example, Peninsula Haven turned to the nuclear Navy as the source of new leadership and, through the new leader, a new organization and culture. We have heard numerous times throughout the industry that a nuclear power plant tends to reflect the style of the vice president, unless the vice president is uninvolved, which is even worse. Programs for improvement, whether labelled revitalization, total quality management, empowerment, or whatever, then tend to flow from the top to the bottom. It is rare for the bottom of the organization to be the origin of programs. Because maintenance is perceived to be a support function staffed by non-professionals, their low status gives them a poor position to argue for resources and attention, despite their critical and costly role and management rhetoric insisting that employees take ownership of their activities.

Finally, associated with many of the above issues is the culture of individual blame and control that permeates industry. The reaction to incidents is to identify an error and blame someone for not following procedures or not paying attention (Carroll, 1995; cf., the fundamental attribution error, Nisbett & Ross, 1980). The typical response is to punish the offender with a few days off without pay, to tighten up training programs to emphasize self-checking, to tighten up procedures to include more detail and more checks, and to involve more people in quality assurance and oversight. Although these steps appear to create more barriers against accidents, they also create more pressure, narrowing of attention, alienation from work, distrust, lack of information flow, redundancy, and higher costs. These may interfere with the need to create a learning organization, which requires a free flow of information and an active, open, curious attitude on the part of all employees (Levitt & March, 1988; Weick, 1987).

Restructuring the Maintenance Game

Let us return to consider the situation at Du Pont. Clearly, they needed a method that could help them understand the dynamic complexity they faced, why past attempts had not worked, and how to design alternative policies -- and they needed to find a way to explain these complex dynamics to the experienced plant operations and maintenance people who had to take action.

Developing New Mental Models

The Du Pont Competitive Position Assessment Team (CPA) began the development of a simulation model to capture the system-wide, dynamic benefits and costs of different maintenance initiatives. The model utilized the system dynamics metholodogy developed at the MIT Sloan

School of Management (Forrester, 1961; Richardson & Pugh, 1981). It was developed interactively by the Du Pont team with the assistance of Mark Paich, an alumnus of MIT's program in system dynamics, now a professor and consultant. Using the model, the team attempted to quantify the net present value (NPV) of maintenance to the business as a whole, accounting for both the direct costs of each maintenance activity and the benefits it delivered over time in terms of increased uptime, more accurate and effective repairs, fewer breakdowns, more cost-efficient management of human resources and supplies, and so forth.

Recent theories of "modeling for learning" (Morecroft & Sterman, 1994; Senge & Sterman, 1991) emphasize the heavy involvement of the client team as partners in model development. The model was used to create an environment for learning, a simulated plant or microworld in which the Du Pont team could experience the long-term effects of current practices, discover for themselves how the present system fails, and try out new policies. The team gradually developed an appreciation of the dynamic complexity of the maintenance system. For example, they realized that by creating eight separate teams, each focused on a distinct area, the CMLT had implicitly assumed that the maintenance function could be partitioned into separable components which did not interact. But clearly the eight areas investigated by the field teams were tightly intertwined, both with one another and with other aspects of plant operations. The best-practice companies, they reasoned, were most likely managing multiple initiatives so that they produced a reinforcing effect, or at a minimum, so that they did not undercut each other.

As an example, consider the ways improving scheduling can raise the productivity of the mechanics. If a team of mechanics is aware of pump maintenance needed on a given day, then the repairs can be performed faster and less expensively than if the work were unscheduled, since the work can be done during normal hours rather than overtime and other work which might physically interfere with the pump maintenance can be avoided. Similarly, materials planning boosts the productivity of scheduled work by preparing kits of parts for scheduled jobs. Predictive maintenance (including vibration monitoring and failure trending) facilitates planning and parts procurement. More predictable demands for parts means less expediting and leaner parts inventories while improving part availability.

Reliability engineering was another dimension that was not being addressed adequately by the CMLT teams. Reliability engineering goes beyond preventing or predicting maintenance by redesigning machinery to be more robust (i.e., perform adequately for longer periods under more difficult conditions), thus reducing the creation of latent defects that can ultimately cause a breakdown. Investment in equipment reliability can reduce the machinery's normal failure rate and thus decrease the required maintenance effort. For example, upgrading to a more durable type of pump seal would improve reliability, allowing maintenance intervals to be lengthened and supplies of replacement seals in inventory to be reduced. The payoff to any of these initiatives is much greater when they are undertaken together rather than separately. Scheduling, for example, does nothing to benefit the unexpected outage.

The Manufacturing Game

The CPA felt that the simulation model and learning process helped them develop new perspectives on the maintenance problem which could improve the contribution of Du Pont's maintenance program to corporate profitability. Now their challenge was to implement the needed changes. In part, the challenge was technical -- for example, to develop workable techniques to design more reliable components. In part, the challenge was managerial -- for example, learning how to schedule predictive and preventive work. But fundamentally, they had to recreate the learning process they had experienced throughout the plants, from top management to the lowest grade mechanics. Their challenge was no less than to create a culture of defect elimination and preventive maintenance in place of the prevailing culture of reactive maintenance.

The Du Pont team's early efforts to communicate the results of their modeling work were mostly unsuccessful. They first tried to explain the model assumptions and show the simulations in traditional presentations, but found "it was difficult to compress the thinking that produced the model into a short period of time....[T]he discussion of the assumptions was often frustrating to the modelers and confusing to the managers."[4] As noticed in other modeling studies (Senge & Sterman, 1991), after going through a long process of learning facilitated by the modeling tools that changed their mental models and cultural understandings of the complex feedback dynamics created by interactions of maintenance with other functions in the organization, the modelers then implicitly expected others to accept these implications for policy after a short presentation. Such presentations are not only limited as a means for communication, but also may trigger resistance: the implied status differential between the new experts and the uninitiated may engage political conflicts and defensive routines (Argyris & Schon, 1978).

The team decided that others must experience the learning process they, as modelers, had. One team member had attended an outside workshop on modeling where he played the "Beer Game," a board game illustrating how the inventory management policies of individual firms can create business cycles (Sterman, 1989b). The team felt that a "maintenance game" experiential learning environment could enable plant personnel at all levels to discover for themselves many of the insights the modeling team had developed, but without the time consuming modeling process. The team drew upon other learning laboratories employing system dynamics simulations in designing the game and workshop (Sterman, 1988, provides an example; Isaacs & Senge, 1992; Kim, 1989; Meadows, 1989; and Senge & Sterman, 1991, discuss the philosophy, design, and pitfalls of learning laboratories).

The day-long Manufacturing Game represents a typical continuous-processing plant on a board of about 4 by 6 feet. There are three players: the Business Services Manager (who runs the parts store room), the Maintenance Manager (who plans, schedules, and allocates resources for

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[4] Material in quotes relating to Du Pont was gathered in interviews by Ellen Banaghan and John Sterman.

maintenance work), and the Operations Manager (responsible for plant profitability and for meeting product demand). Chips represent equipment, product, parts, maintenance resources (such as mechanics), latent defects, and overtime or contractors. Equipment chips move through the operations sector. Each chip produces product and gradually accumulates latent defects. Eventually equipment with defects breaks down and enters a queue of equipment awaiting repair. Repairs can only be performed if maintenance resources (mechanics and parts) are available, requiring either coordination between the maintenance and stores managers or expensive overtime and expediting of parts procurement. The maintenance manager can also choose to attack defects through preventive maintenance. However, preventive maintenance requires that the operations manager take functioning equipment out of service (a planned outage) so the preventive work can be performed. Often, the operations manager refuses precisely because so much equipment is broken down that all remaining equipment is needed to meet demand, thus further deferring preventive maintenance and causing still more breakdowns.

Effective learning from a simulation game requires more than game play (Brehmer, 1990; Diehl & Sterman, 1995; Paich & Sterman, 1993); the game experience must be embedded in a structured learning cycle including conceptualization, experimentation, reflection, and re-conceptualization. The learning laboratory developed by the Du Pont team provides participants with a chance to share experiences and ideas about maintenance issues with colleagues from other functions; to develop skills in conceptualizing and representing their knowledge of maintenance dynamics, and to use these skills to develop and improve common mental models; to test programs and policies to improve maintenance (in the game) that they can not test in the real plants; and finally to learn how the insights developed in the learning lab can be implemented.

The response to the model, game, and learning lab has been enthusiastic. Thousands of Du Pont personnel have participated in the learning lab. Over thirty people are now qualified as facilitators to run the game and learning laboratory. For many Du Pont employees, the learning lab is their first chance to reflect on these issues and participate in the design of the structures, routines, incentives, and metrics that govern their work. The learning lab integrates the cognitive skills involved in understanding the dynamics of a complex feedback system with teamwork, group interaction and inquiry skills, and the emotions required for implementation and culture change. The learning lab now includes skits, games, and songs about eliminating defects as means to surface and legitimate discussion of the full range of issues important for successful plant-wide improvement of maintenance.

Implementing New Programs

After a team at a particular plant experiences the learning lab they are trained in an implementation program to translate the insights of the game into actual improvement. The pilot implementation program focused on pumps and was named "Pumps Running." Pumps were selected because they are common and important to the plants, consume a significant share of maintenance effort, and are subject to significant wear, suggesting a potential for large improvements in plant uptime by monitoring wear and investing in reliability engineering to examine the use of better parts (such as improved seals and bearings). The installation of duplicate pumps in response to poor pump reliability illustrates how a culture of low reliability and reactive maintenance had become so pervasive in some sites that the entire organization had adapted to it -- at great cost -- rather than correcting it. And, the presence of duplicate pumps allowed the new proactive maintenance policy to be tested without adversely affecting production.

Results to date have been quite encouraging. More than 10 different product lines in 7 plants have participated in the learning laboratory and implemented the Pumps Running program. Table 3 shows the average improvement in MTBR to date among participating plants is about 17% per doubling of pump experience[5], with maintenance costs during the same period falling by an

[5] The apparent rate of improvement was faster initially than later, reflecting the fact that the worst performing pumps, with the greatest scope for improvement, are likely to fail first and thus be enrolled in the program before intrinsically more reliable pumps. As the better-performing pumps

average of 21%. Comparable non-participating plants have improved at a rate of only about 4% and have experienced a large increase in associated maintenance expenses[6]. It is noteworthy that one site, Plant C Product Line 6, decided to pursue a technical improvement program driven by the industrial engineering staff. This program, which did not explicitly address the issue of the culture or mental models of the workforce, has resulted in virtually no improvement while costs have increased dramatically.

Insert Table 3

The success to date of the maintenance game and pumps running program has generated its own challenges. In particular, although the maintenance game may alter mental models, the implementation of change generates its own dynamic reactions that may undermine the benefits. In essence, the maintenance game is not easily separable from a larger "organization game." The Du Pont team continually revise the game, learning lab, and implementation protocols as new issues come to light, such as:

Countervailing reward systems. For mechanics high on the priority list to receive overtime in their present work groups, transferring to a proactive maintenance group would mean losing lucrative overtime. The Preventive/Predictive Maintenance manager at one plant said, "when an outage comes and [they] have a chance to work 14 -16 hours per week overtime they say `to hell with this vibration [monitoring] stuff, I'm going to the outage area.'" A foreman noted, "I heard

gradually get added to the program the potential improvement falls. Such behavior is typical of improvement dynamics and reflects what Total Quality advocates call "picking the low hanging fruit."

[6] Plants enrolled in the program were not selected randomly; thus plants choosing to participate may have been predisposed to change. Nevertheless, the differences in improvement rates and costs between participant and nonparticipant plants are large and highly suggestive of the benefits of the program.

of a predictive maintenance guy getting kicked out of his group for taking a vibration reading on a down pump."

Turf and status. People are suspicious and biased about the skill sets, education and intentions of workers in other functions. For example, operators complained they could not get into the databases that record equipment histories and other information useful for planning and scheduling proactive maintenance. Some people in the plant believe if you allow operators or mechanics to add equipment histories to the data base "they'll mess it up." These issues involve turf, work rules, and status distinctions among different types of personnel in the plants. These suspicions would be alleviated if people understood the principle espoused by Will Rogers, not usually considered a management theorist: "Everybody is ignorant, only on different subjects."

Loss of challenging work. Mechanics who can handle the most difficult corrective situations are the heroes; proactive work is seen as less challenging and requiring less experience. A shift to preventive maintenance will initially be even more challenging and enjoyable, as preventive work uncovers additional latent defects. But as reliability improves, fewer latent defects will be created, and maintenance work will increasingly be planned and routine. Team members asked, "Could you get people to do inspections such that three-fourths of the time they'll find nothing?"

Job security and cost cutting. The leader of the Du Pont team noted: "many of the mechanics are threatened by pumps running. If maintenance can be done with half as many mechanics, doesn't that mean the mechanics are being asked to work themselves out of a job?" The simulation model shows that it is more profitable for the business as a whole to keep a full complement of mechanics and incur greater costs in the maintenance function than to reduce costs by eliminating mechanics: extra mechanics contribute more to plant uptime and hence revenues than they cost; reducing mechanics could cause a collapse in the commitment of plant personnel to the proactive maintenance program; and without slack, a run of bad luck means the remaining mechanics must be reallocated from proactive maintenance to reactive maintenance, which triggers the vicious spiral again. Yet the mental models of managers are strongly conditioned by cost-cutting pressure to pare back resources when there no longer appears to be a need. A team member worried that "As soon as you get the problems down people will be taken away from the effort and the problems will go back up."

The concern that management would cease taking the medicine (maintaining slack in the maintenance function) once the symptoms of illness (a high breakdown rate) disappeared is well-founded: medical patients often stop taking the drugs that control their blood pressure after noting that their pressure has in fact dropped within normal levels (Caldwell, et al., 1970), patients do not take the full regimen of antibiotics once they feel healthy, and so forth. Such behavior reflects a poor mental model of the relationships among symptoms, disease, and treatment. Indeed, the nuclear power industry is particularly concerned with complacency, which is the reduction in attentiveness when problems appear to have been solved (IAEA, 1991). Changing the mental models of management and employees thus remains a major challenge for the team as the pilot programs generate results.

Differences Between Chemical and Nuclear Power Plants

Although we have told the stories of Du Pont and Peninsula Haven in order to emphasize their similarities, Peninsula Haven and the nuclear power industry in general face some additional challenges in their efforts to improve their performance.

In the chemical industry a reliability data base which reveals information about mean time between failures and the mean time to repair has been very valuable in predicting failure probabilities for functions and systems. However, in the nuclear industry, this type of data base has only proved to be very useful in a few special cases such as that of the small components used in instrumentation and control applications. In other cases where general performance statistics have been compiled to target corrective actions and refine preventive maintenance programs, maintenance specialists have found the data to be too simple and often inaccurate. The specialists have had to carefully design very elaborate reliability studies that take into account the mixture of modified and unmodified equipment used in plants or the mixture of equipment of slightly different designs and vintages. The customizing of large components that exist in very small numbers makes the application of a typical reliability study in a nuclear context doubtful.

Colonial had difficulty reducing its maintenance backlog, in part, because of the lack of spare parts inventory. Sales have dropped off for the vendors since plant construction halted in the U.S. and many of them have gone out of business. Finding replacement parts of the same quality and type often is difficult. The use of slightly different replacement parts requires a time-consuming modification process involving design changes and approvals at many levels. If the repair is so big as to be designated a capital improvement, then even more layers of approval are necessary. Rather than go through the process of receiving approval for a request for a permanent modification, they will get approval for a temporary modification and a time extension.

Japanese nuclear power plants are known for their preventive maintenance programs that are designed to guarantee long-term component and plant reliability which contribute to low reactor trip and forced outage rates. The Japanese planned unavailability rate from 1979-86 was high, about 35%, but their strategy was meant to reduce the forced shutdown rate to the lowest extent possible (it was below 5%). In contrast, Germany, France, and the U.S. had planned unavailability rates of about 20%, but their forced unavailability rates were higher: Germany at about 12%, France at 15%, and the U.S. at 20%.

The Japanese accomplish the low forced shutdown rate through 10-year maintenance plans which identify and schedule necessary preventive maintenance for essentially all plant equipment, and an industrial system that supports preventive maintenance practices (Carroll et al., 1992; INPO, 1985; Yakura, 1995). Their strong preventive maintenance programs depend on close relationship with the plant manufacturer who is the prime contractor for annual outage inspection work. Manufacturing engineers are on site monitoring equipment conditions and making suggestions for improvements. The manufacturer plans and carries out major maintenance projects; after an unexplained shutdown, is the manufacturer that organizes the special inspection team and determines the corrective actions. Sub-contractor maintenance teams, which are involved in the original construction of a reactor, are usually hired for the life-time of the plant to carry out all maintenance activities on the piece of equipment that they helped construct. These relationships are part of the Japanese industrial system that emphasizes long-term planning, long-term relationships among companies, long-term employment contracts and worker commitment, and a cooperative approach to government-industry issues including regulation. Cost-cutting pressures are far reduced: the Japanese nuclear industry is considered an essential national resource and utilites are allowed to charge generous rates to cutomers. The Japanese example shows that a proactive maintenance culture with a long-term orientation is possible, and the result is indeed a reduction of corrective maintenance. However, the Japanese operating strategy is supported by financial resources and cultural values that may not be sustainable as Japan undergoes social and political changes.

Conclusions

Mental Models

The Du Pont and Peninsula Haven stories show an underlying structural similarity or theme: it is difficult to establish and maintain preventive maintenance practices in the face of continuing pressure for immediate production and cost-cutting efficiencies. These difficulties are exacerbated by the mental models of employees from top to bottom of the organization that conceptualize highly-interdependent, dynamic processes as if they can be decomposed into separable functions and discrete events. When things go wrong, the lessons learned do not penetrate these mental models, but are associated with a particular person who made an error or leadership deficiencies in the abstract. Because these mental models fit into the work practices, culture, career paths, and physical structure of the plant, there is a system of assumptions and behaviors that is difficult to change. Indeed, expensive multi-year efforts to bring about improvements at both Du Pont and Peninsula Haven had not succeeded.

Rational and Irrational Decisions

It seems reasonable to conclude that neglect of preventive maintenance and other symptoms of incomplete, short-term mental models leads to decisions that are irrational from an organizational viewpoint. Information is available from which to design better strategies and practices. Yet, the strategic and operational levels of the organization do not easily integrate their concerns and feedback in order to improve. Indeed, both Du Pont and Peninsula Haven seemed to have organizational structures and incentives that made it individually rational (at least in the short run, and in terms of accepted logics within the organization) to preserve the defective practices. What seems necessary, then, to align individual and organizational rationality is, first, to change mental models so as to create understanding of longer-term global issues and, second, to change work practices and organizations based on these new understandings.

Changing Mental Models

At Du Pont, the recent successful program to restructure the maintenance function did not stop at an analysis of the problem by technical experts who would then design a program to change work practices. Instead, they initiated an effort to change the way maintenance was understood from top to bottom of the organization. They have succeeded at changing mental models through an experiential game that provides a complex, dynamic learning environment in which employees enact old and new practices and receive feedback in a form and context that encourages learning. But the Manufacturing Game alone is not sufficient to change mental models; it is accompanied by opportunities to share experiences and develop skills in legitimized ways.

Changing Work Practices and Organizations

Perhaps most difficult of all is to translate changes of mental models into changes of work practice that produce operational improvements. New mental models are only the groundwork for the seeds of change; necessary but not sufficient. The success of the Pumps Running program depended on the Manufacturing Game but added a well-crafted program that suited the organization. In a sense, implementation is an Organization Game within which the Manufacturing Game is played. As we have shown, resistance to changes in maintenance emerge after initial success from employee motivations, career paths, power structures, and complacency.

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Table 1

Selected Results of the Du Pont Benchmarking Study

Performance measures	Du Pont relative to industry leaders
Maintenance Cost per $ of plant value, ERV (Estimated Replacement Value)	+10% to 30%
Mechanics per $ of plant ERV	+23%
Maintenance Planners per $ of plant ERV	-55%
Maintenance support staff per $ plant ERV	-15%
Flexibility of maintenance work force (ability to do work outside of job categories)	-70%

Source: Flynn, V. (1992).

Table 2

Maintenance Backlogs at Peninsula Haven and the Nuclear Industry

	Colonial	A.Grant	Industry
Corrective Maintenance	50%	50%	50%
Preventive Maintenance	25%	3%	3%

Source: "Comparative Performance Indicator Report" of Peninsula Haven. Exact numbers have been modified to maintain confidentiality.

Table 3

Improvement in Mean Time Between Repair (MTBR) for Plants and Product Lines

Implementing the Maintenance Game and Pumps Running Compared to Control Plants

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Plants Implementing the Maintenance Game and Pumps Running

Plants/Product Lines	Improvement rate in MTBR[a]	Change in Costs[b]
Plant A Product 1	16%	-16%
Plant A Product 2	14%	-13%
Plant A Product 3	23%	-43%
Plant B Product 4	16%	-25%
Plant C Product 1	18%	-10%
Plant D Product 5	13%	-23%

Comparison Plants Not Using Maintenance Game/Pumps Running

Plants/Product Lines	Improvement rate in MTBR[a]	Change in Costs[b]
Plant C Product 2	8%	+5%
Plant C Product 6	0%	+70%

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[a] The improvement rate is the % increase in MTBR per doubling of cumulative experience with pumps in the program.

[b] The change in costs is the total change in labor and materials costs associated with the maintenance of the pumps in the program.