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Total Productive Maintenance

TPM

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06 January 2009

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26 July 2008

Introduction

Total Productive Maintenance (TPM) is the maintenance sub-system of Lean Manufacturing. TPM improves manufacturing performance by reducing cost, improving quality and increasing productivity.

As with other parts of Lean, TPM borrows tools and techniques from other disciplines as well as previously developed and proven maintenance techniques. The combination, integrated as a system and further integrated with the larger Lean system, produces results far beyond the individual techniques; i.e., the system is more than the sum of its parts.

Losses & Cost Avoidance

In one sense, everything in maintenance is waste since none of it directly contributes to the customer's needs and wants. While a perfect factory with perfect equipment would need zero maintenance effort, real factories and real equipment need maintenance to function. Without it, they create further waste in lost time and defects. The objective of TPM is to minimize the total waste or, in TPM terms, loss.

Figure 1 Maintenance Losses

Maintenance-related losses come in many forms. Accounting systems show some costs (losses) but others remain hidden as in figure 1. For example, the exact cost of maintenance labor and parts is easy to track. The cost of a defective part is somewhat easy to track but the "commotion cost" of the defect is nearly impossible to track and usually much greater. For an example, see: The True Cost of Defective Quality.

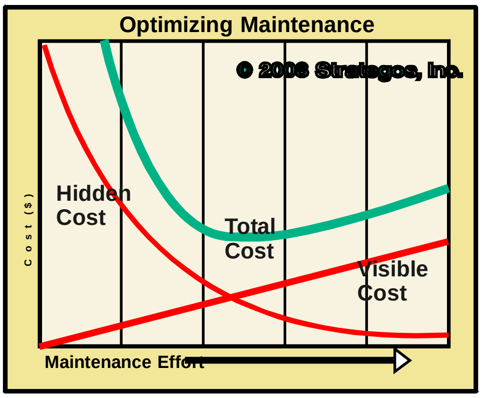


Figure 2 Optimizing Maintenance Cost

The trick is to find the balance between direct maintenance expenditures and the hidden costs while ensuring that maintenance resources are effectively used. Analytically and quantitatively, this is very difficult. From this author's experience and observation, however, few (if any) factories spend too much on maintenance. Most operate far to the left on the total Cost Curve of figure 2. Well-managed maintenance is nearly always a good investment.

The Origins of TPM

The demands for predictable machine performance in Lean Manufacturing led to the development of TPM. Early on, the people at Toyota must have realized that many quality problems and setup problems originated in poor maintenance. Total Quality Techniques, Statistical Process Control (SPC) and problem solving teams transferred well to maintenance issues. Reliability Centered Maintenance (RCM) also contributed. Reliability Centered Maintenance developed from the military's development of Reliability theory that, in turn, came from statistical theory. Statistical theory also contributed to the development of SPC. The use of problem solving teams came from Eric Trist's Socio-Technical Systems as well as from Reg Revans' Action Learning.

Figure 3 illustrates this simplified summary of TPM's development.

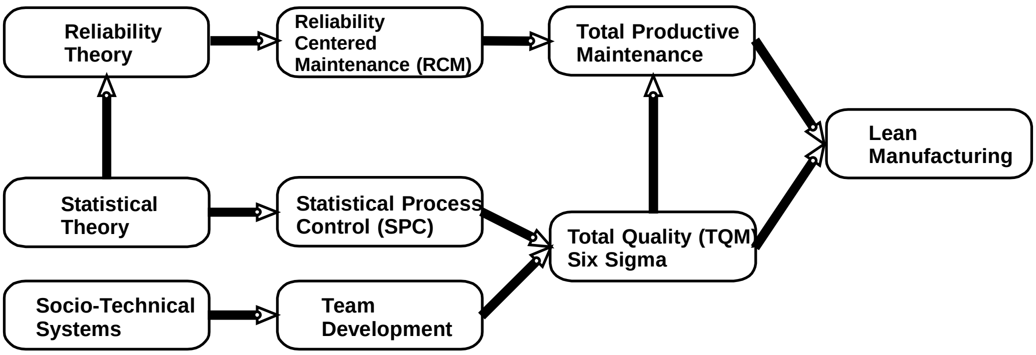


Figure 3 The Origins of TPM

Results

Some years ago I was Maintenance Superintendant in a large, 100-year-old steel foundry. We employed most of the principles, tools and techniques of TPM long before they had names. The results were excellent. For example, our average downtime on overhead cranes went from about 17% to 2.5%. Other major equipment showed comparable results. Here are some other results reported by industry:

- MRC Bearings reduced unplanned downtime by 98% in one cell and 99% in another - all within one year.
- Monsanto runs their three-year old TPM start-up plant at 97% on-stream time while most other units run between 85% and 90%.
- 3M reduced their maintenance cost by 60% within three years.
- DuPont reduced off-quality by 69% and improved capacity by 29% in three years.

- Harley-Davidson estimates that the ROI from TPM has been ten-fold to the cost of implementation.
- Kodak reported a $5 million investment in TPM that resulted in a $16 million increase in profits.

Reliability & Reliability Centered Maintenance

Beginning in World War II, the War Department sponsored a new science called Reliability. Reliability is the science of maintenance. It uses statistics and failure theory to measure, understand and improve the performance of equipment and maintenance. Reliability theory can guide engineers as they design and test new equipment. After equipment has been in service, reliability data tells the maintenance engineer how to improve its performance.

As the Gulf Wars demonstrated, this science has produced outstanding results in defense. Regrettably, little of this knowledge has found its way into industry. Most maintenance operations still operate on the principal of "if it ain't broke, don't fix it".

Mission Reliability

Figure 4 Mission Reliability

Question: If we dispatch 1000 heavy bombers for an 8-hour mission, what percentage will complete the mission without mechanical failure?

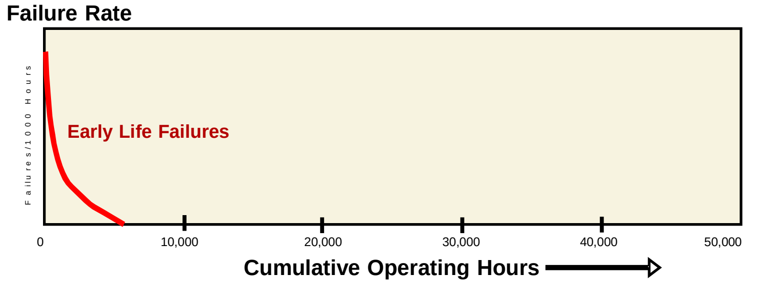
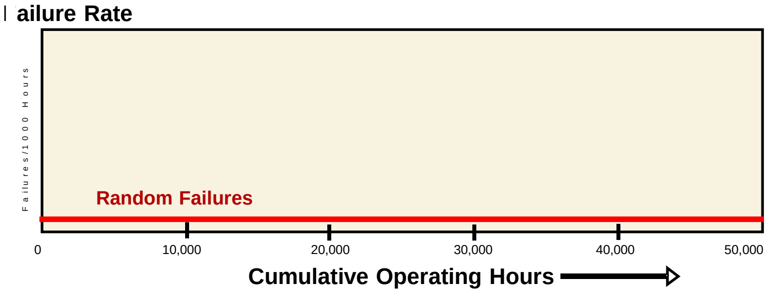
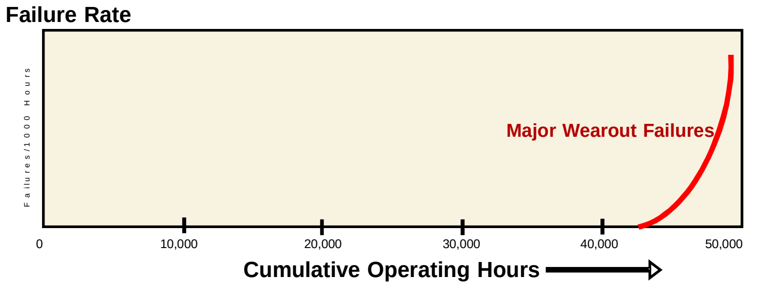
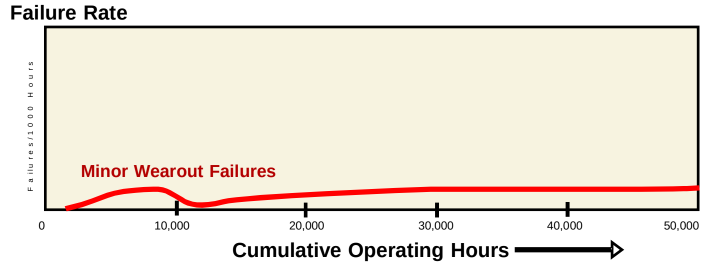
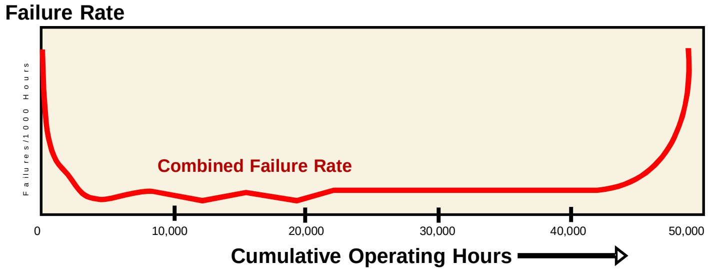
Reliability Metrics

Reliability uses many metrics for evaluating equipment and systems. The original metric, Mission Reliability, answered the question of figure 4. For industrial maintenance, the metric of Failure Rate is usually more relevant. Failure rate is the number of failures per 1000 hours of operation. It can apply to a complex system such as a machine tool or it can apply to a large number of simple components such as light bulbs. For this discussion focuses on individual units of complex equipment.

Failure Modes

Failures occur in one of several modes. Understanding modes and what mode is the likely cause for specific failures is important because different approaches or strategies may be more or less effective on the various modes. Table 1 summarizes the various failure modes and illustrates their characteristic failure rates over time.

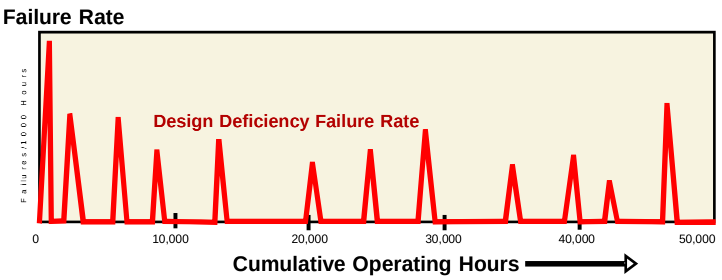
Table 1 Failure Modes & Characteristics

Failure Mode	Failure Rate Curve
Early Life These occur when equipment is placed in service. Causes are sub-standard components and/or improper installation. Early life failures occur frequently when the equipment is first placed in service and then rapidly decline.	
Random Failures ...result from variations in both the load imposed on any given component and the variations in strengths of supposedly identical components. Random failure rates are essentially constant over the life of the equipment, normally small and overshadowed in most practical cases by other failure modes.	
Major Wearout This occurs when major sub-systems or structures become worn or weakened to the point that proper repair is impossible or impractical. Failure rate begins to rise sharply and the only solution is major overhaul or replacement.	
Minor Wearout Complex equipment requires replacement of components as each component reaches its individual wearout life. Since components have different lives and are changed at different times, the failure rate tends to be relatively constant and mimics the random failure rate curve.	
Early Life, Random & Wearout When the previous failure modes are combined, the result is the "Bathtub Curve", familiar to many.	

Design Deficiency

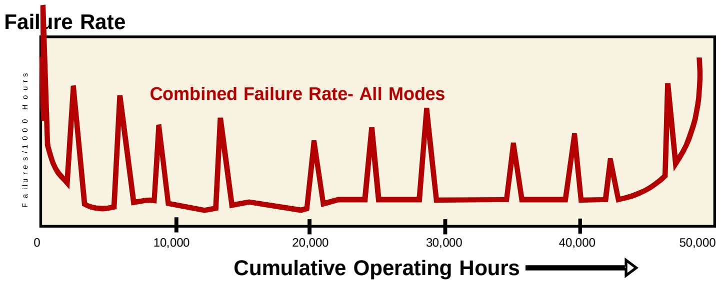
This type of failure is the result of design error and shows up as a series of wearout failures. This type of failure does not occur on equipment that has been extensively tested and developed. It is inevitable on new designs that have not been thoroughly tested and on the "special" machines that are often used in industry.

The worst problems will normally be corrected early on until the failure rate is reduced to a tolerable level. At that point, remaining design deficiencies are indistinguishable from minor wearout failure.



All Modes Combined

With all modes combined, the failure curve is the familiar bathtub but with spikes of increased failures at irregular time. Determining the mode for specific failures requires additional investigation and cannot be determined from the failure curve alone.



Equipment Reliability Metrics

Metrics help to focus efforts on the most critical equipment rather than reacting to the crisis de jour. They measure progress and help to adjust efforts accordingly. They are critical for identifying and resolving specific problems. Equipment metrics can be surprisingly simple. Only three data elements, collected for each machine and analyzed properly, are really necessary for most situations.

This discussion is about the metrics for machine performance. It does not include metrics of maintenance department productivity, budgeting or cost allocation. Such additional metrics are required to operate a maintenance department effectively.

All these metrics are most effective in graphical form. They are not very meaningful as individual numbers. However, in the context of past and future, trends, anomalies and patterns reveal themselves.

All of the first four metrics, the most useful, derive from three numbers. Assuming a calculation period of one week, the following questions must be answered:

- How many breakdowns (failures) did we have this week?
- How long did each breakdown take to repair?
- How many hours were scheduled for the equipment?

Calculations and tracking can be further simplified by assuming that each machine is scheduled for about the same production (say 40 or 80 hours) and simply using one week as the time bucket.

Table 2 Equipment Metrics

Name	Symbol	Description	Formula
Failure Rate	λ (lambda)	Failure rate is one of the simplest and most useful metrics for machine performance. Using a week, month or other convenient period in place of actual operating hours can approximate it. If data is accumulated on a (say) weekly basis, the only input is the number of breakdowns during that week.	$\lambda = \frac{\text{\# Failures}}{\text{Operating Hours}} \approx \text{\# Breakdowns/Week}$
Mean-Time-Between-Failure	MTBF	MTBF is also a metric for machine performance. It is the inverse of Failure Rate and is thus calculated from the same parameters. It is a meaningful metric for long periods of time but not suitable for daily or weekly monitoring. If there are no breakdowns in a given period, the MTBF for that period is mathematically "undefined."	$MTBF = \frac{\text{Operating Hours}}{\text{\# Failures}} = \frac{1}{\lambda}$
Mean-Time-To-Repair	MTTR	Mean-Time-To-Repair is another simple yet valuable metric for industrial maintenance. It reflects both the severity of breakdowns and the efficacy of repair activities.	$MTTR = \frac{\sum(\text{Breakdown Times})}{\text{\# Breakdowns}}$
Availability	A	Availability is the portion or percentage of time that equipment is available for operation. It is commonly referred to as "Uptime". Availability is another useful metric for industrial maintenance and you will want to track it along with Failure Rate and MTTR. Availability derives from the same data collected for MTTR and Failure Rate. It is easy to calculate.	$A = \frac{MTBF}{MTBF + MTTR}$
Reliability	R(T)	Reliability is the probability that equipment will complete a mission of length "t" without failure. It is an exponential function. Reliability has limited use for most industrial maintenance although it is important for military and other applications.	$R(T) = e^{-\lambda T}$
Overall Equipment Effective-ness	OEE	Overall-Equipment-Effectiveness is a new metric that has received considerable publicity in recent years. It attempts to capture all the parameters in a single measure. However, the practical application is somewhat limited.	OEE = Availability X Performance Efficiency X Rate of Quality Products

Maintenance Strategies

Several strategies or approaches are available for improving the maintenance or breakdown performance of equipment. These are: Breakdown, IRAN (Inspect & Repair As Necessary), Predictive and Redesign. Table 3 summarizes these strategies.

Table 3 Maintenance Strategies

Maintenance Strategies

Strategy	Description	Examples	Use When
Breakdown	Do nothing until equipment fails. When failure occurs, repair as required.	✍Replace jib hoist when hoist fails. Overhaul hoist in shop and use as spare. ✍Replace nut runners when they fail. ✍Replace light switches when they fail.	✍Breakdown cost is low. ✍Components are cheap. ✍Replacement is easy. ✍Inspection is difficult. ✍Failures do not cascade.
IRAN (Inspect-And-Repair As-Necessary)	Inspect on schedule to detect imminent failure. Replace or repair before failure. Often combined with scheduled service such as lubrication.	✍Inspect for visible cracks while lubricating. ✍Inspect V-belts for cracks or fraying. ✍Check air pressure in tires & tread for wear. ✍Visual inspect contacts on motor starter and replace when pitted.	✍Inspection is easy. ✍Incipient failure is evident before actual failure. ✍Wearout highly variable.
Predictive	Monitor equipment and components with long-range predictive techniques such as vibration analysis, infrared or known wear-out life. Replace prior to failure.	✍Overhaul aircraft engine after 5000 hours. ✍Replace filters every three months. ✍Group re-lamp office areas. ✍Monitor bearing vibration signature and replace as indicated. ✍Monitor infrared signature of electric motor and replace as indicated.	✍Failure is catastrophic. ✍Wearout is predictable. ✍Replacement is inexpensive.
Redesign	Equipment is redesigned with more robust components, to increase reliability, make inspection easier or make replacement easier.	✍Pendant controls on overhead crane are redesigned with quick-connectors and shock protection to reduce failures and make replacement quick. ✍Motor starter size increased. ✍Electrical cabinets on overhead crane mounted on vibration dampers.	✍MTTR & failure cost is high. ✍Failure Rate is high. ✍Inspection is difficult.

The best strategy for a particular machine or situation depends, partly, on the failure mode being experienced. For example, IRAN is seldom effective for preventing early life failures. These rarely give warning and there is no history to draw upon. Early life failures must be addressed in the original design and also in the original manufacture and test of the equipment. Once in service, about all you can do is wait until something breaks. This is why one of the "Pillars of TPM" is new equipment management.

Table 4 shows which strategies usually apply to each failure mode.

Maintenance Strategies	Breakdown	IRAN	Predictive	Redesign
Early Life	X			X
Random	X	X		X
Minor Wearout		X		X
Major Wearout		X	X	X
Design Deficiency		X		X

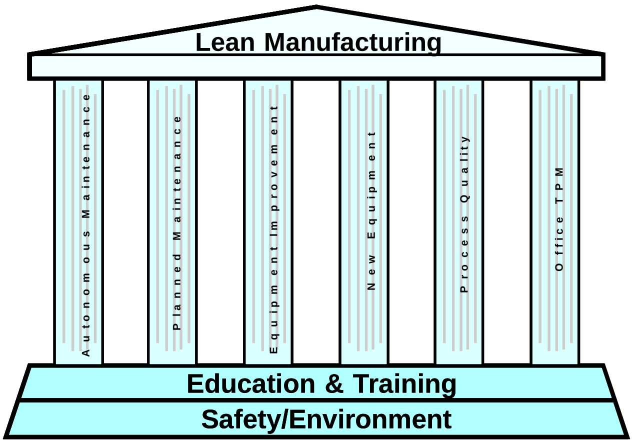
Table 4 Strategies & Failure Modes

Note that the redesign (design) strategy applies to all failure modes. Throughout the equipment life, proper design and then redesign as required is the most critical element for ensuring equipment performance. Yet capital equipment is often purchased using price as the primary decision factor.

Pillars of TPM

Total Productive Maintenance is often presented as a series of pillars supporting Lean Manufacturing and resting on a foundation of education and training. Below this is the attitude of environmental responsibility and safety. Figure 5 illustrates. This representation is adequate as a starting point. However, TPM, like Lean itself, is a dynamical system and cannot be fully understood with a static model.

Figure 4 The Pillars of TPM



Supporting Lean

Maintenance enables and supports Lean efforts in at least three major ways: Quality, Setup Reduction (SMED) and predictability. In turn, other Lean elements support TPM through Workcells, Teamwork and Problem-solving.

The Foundations

Education & Training—Education, training and investments in people characterize all aspects of Lean. In the maintenance area, they are even more important because of the specialized knowledge required on typical manufacturing equipment. This is one of the foundation stones of TPM. Without it, the pillars of TPM will have limited impact.

Safety/Environment— Underlying even the training and education piece are the more fundamental values of responsibility to the environment and safety for employees. One important reason is simple: it is the right thing to do.

A more pragmatic reason involves motivation. Most people want to be a part of something larger than themselves; appeals to higher motivation bring involvement and commitment. It is difficult to argue against safety and a common commitment to safety can be a bond that brings people together on other issues.

Autonomous Maintenance

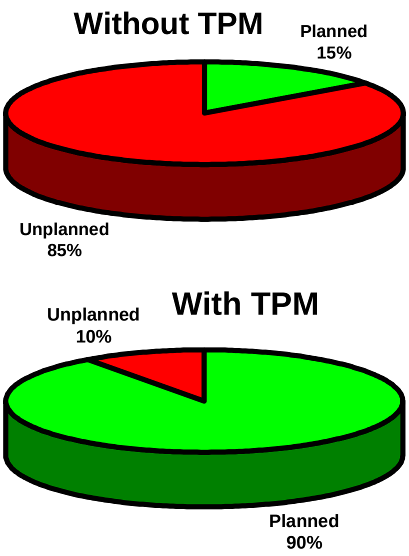
Autonomous maintenance is the concept that the people who operate a machine should maintain the machine. The degree of autonomous maintenance depends on the level of training and the abilities of operators. It often starts with basic lubrication, cleaning and inspection and then graduates to minor or even major repairs.

For example, in the foundry where this author worked, machinists repaired and overhauled their own machine tools. A trained and competent machinist is certainly capable of overhauling a gearbox. And, as the users, they tended to know the equipment intimately. In the military, everyone cleans their own weapon. When their life depends on proper functioning, people take more care.

Autonomous maintenance frees resources in the maintenance department for the other activities such as equipment improvement or major overhauls. It amplifies the maintenance efforts and involves the operators who then take better care of the equipment.

Planned Maintenance

Figure 5 Planned & Unplanned Maintenance



Planned maintenance is the deliberate planning and scheduling of maintenance activities as opposed to reacting to breakdowns and emergencies. A maintenance department that uses TPM effectively generally devotes less than 10% of its labor hours to such unplanned activities. Without TPM it is not unusual for 80%-90% of the labor to be unplanned.

Unplanned maintenance is a strong indicator that prevention and improvement programs are non-existent or ineffective. In addition, high percentages of unplanned maintenance creates, among others, the following problems:

- **Huge inefficiencies in maintenance labor.**
- **Confusion and disturbance in scheduling, production and other areas.**
- **Morale problems.**

Equipment Improvement

Improving equipment constantly is a major part of TPM. This author witnessed an outstanding example of this some years ago at Toyota's Kamigo Engine plant. Toyota was using the same type of American equipment that I had seen at Ford Motor Company years earlier. However, Toyota's equipment was so reliable that it ran with far fewer people and far better quality. For more on this see Kamigo engine Plant, 1985.

Most production equipment has not had the extensive design, testing and development common in mass-produced products such as automobiles. Accordingly, there are many deficiencies that may not be evident when the equipment first goes into service. In addition, each manufacturing plant and its products tends to be different and can benefit by design changes that adapt the machines better to their individual situations.

Older equipment does not necessarily have to be replaced. In many cases, it can be upgraded, overhauled and made better than new. In our steel foundry, we did this with fourteen of our overhead cranes. Some were upgraded and re-rated for heavier capacity. All were fitted with new controls, structural deficiencies were fixed and the cranes made better than new. Several of these cranes were over 45 years old.

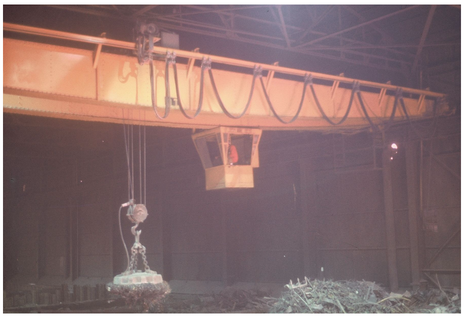


Figure 6 Steel Foundry Crane

New Equipment Management

New equipment management is related somewhat to equipment improvement. It refers to the careful design, selection and testing of equipment. The purpose is to ensure a smooth commissioning process with minimal design defects and problems.

New equipment management includes vendor selection, evaluating options for maintainability, training personnel in advance and other common-sense techniques.

Debugging Rollover

First Pour

Figure 7 Foundry Startup

Process Quality Management

In TPM making the equipment run is only part of Maintenance's job. Ensuring that the equipment is capable of producing parts well within the tolerance range, process capability, is also a primary responsibility.

Worn bearings and ways, undo vibration, bent shafts and multiple other maintenance problems contribute to the gradual deterioration of process capability. With constant use, machines still run but become "finicky." For example, a particular machine shop lathe that the author recalls could only be run by a particular operator. He was the only one who knew exactly where the ways were worn and how to compensate.

Office TPM

TPM also attempts to carry these principles into the office. This might be stretching the concept a little too far as other paradigms are likely to be more applicable.

The Dynamics of TPM

Systems thinking In TPM

The static model of (figure 5) is a starting point for understanding TPM. But pillars on the Parthenon do not fully explain the concept or the effects. TPM is a dynamical system with reinforcing loops and interactions. The various "pillars" interact with each other and with other aspects of the larger production system. When properly designed and executed, the results are far beyond those that would be expected from summing the individual parts.

Figures 9 and 10 attempt to show these dynamic effects. While these figures improve upon the static model, they are also incomplete and, still, not totally adequate. Notice that the elements of figure 9 partly involve equipment and technology and partly involve humans and psychology. This reflects the Socio-Technical nature of the system.

Virtuous Circles In TPM

Figure 9 is a causal diagram. The arrows indicate causal connections between various effects. Plus or minus signs show whether the causality tends to increase or decrease the effect. The numbers identify each causality arrow for purposes of discussion. For example, arrow #2 indicates that fewer breakdowns will increase the maintenance resources that are available.

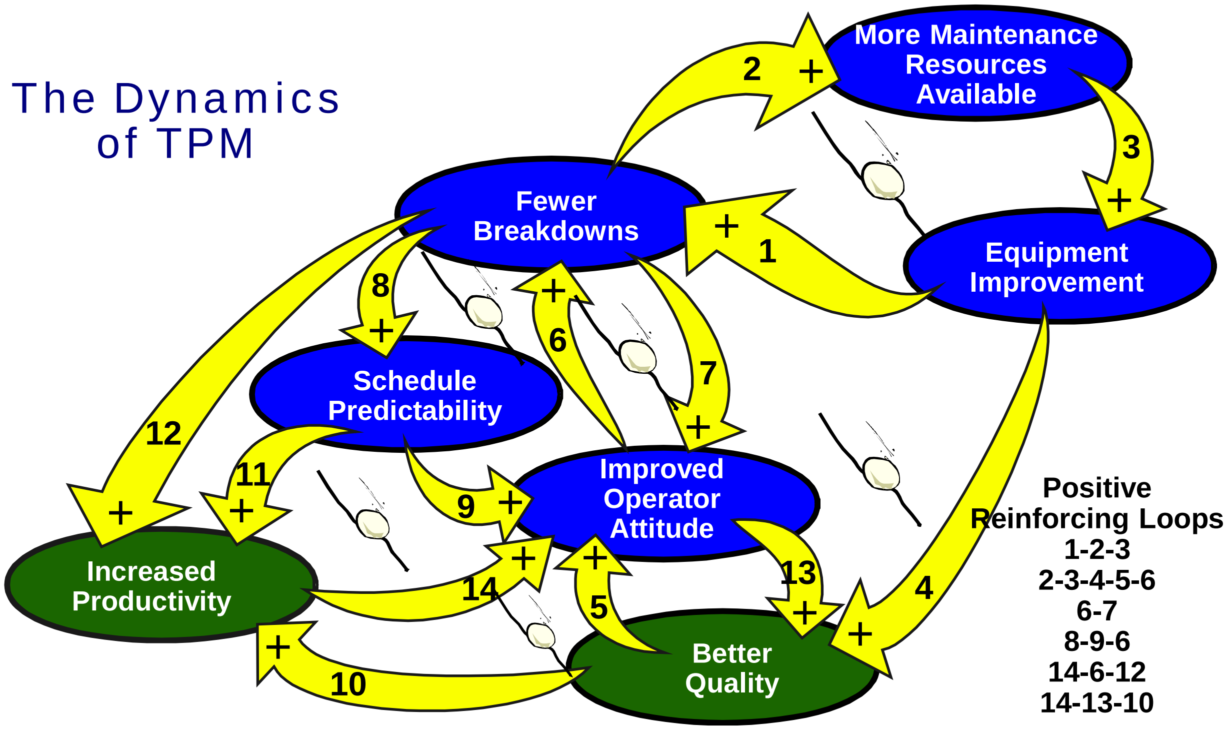


Figure 8 Causal Diagram

The Causal Arrows:

1. **When the condition of equipment improves, it results in fewer breakdowns.**

2. **With fewer breakdowns, less time is required from maintenance to respond to emergencies. This makes more maintenance resources available.**
3. **With additional resources, maintenance can work more on equipment improvement with overhauls, redesign and improved service.**
4. **When equipment improves, quality is better.**
5. **Better quality improves operator attitudes.**
6. **With improved attitudes, operators take better care of the equipment and prevent more breakdowns.**
7. **Fewer breakdowns reduce operator frustration and improve operator attitudes.**
8. **Fewer breakdowns lead to more predictability in the schedule, e.g. fewer changes and rush jobs.**
9. **Increased schedule predictability and stability reduces operator frustration and improves operator attitudes.**
10. **Improved quality leads to more productivity.**
11. **Improved schedule predictability increases productivity since less time is wasted on unnecessary changeovers, coordination and general commotion.**
12. **Fewer breakdowns increase equipment availability and bring increased productivity.**
13. **Improved operator attitudes bring improved quality through more attention and dedication.**
14. **Increased productivity improves operator attitudes--everyone wants to do a good job.**

Figure 9 has at least six reinforcing feedback loops. In such loops, one element increases another, which in turn, increases the first. Like a snowball rolling down hill it continuously builds and, as it builds, rolls faster, and thus, grows faster. The strange little icons within this diagram represent a rolling snowball. This snowball effect is the mechanism behind most exponential growth curves.

Fallacies of The Parthenon Model

Models Influence Thinking

A difficulty with models of any sort is that people tend to identify them with the real system. But, as Alfred Korzybski stated, "The map is not the territory." Models, by their nature are simplified versions of reality. They approximate certain aspects of reality and ignore others. This simplifies our perception and makes the problem comprehensible. The danger is that some of the ignored aspects are, in fact, critical to the issue we are trying to understand. Deming's quote (above) also relates to this.

The fallacies that a model introduces are often hazardous because they are subtle and unconscious. Not knowing what you do not know is a most dangerous situation as Oedipus discovered in early Greek tragedy,

System Robustness

If we take the Parthenon model of TPM too literally, it implies that the TPM system is quite robust. It implies that each pillar is independent. A crack in the column or even a missing column seems unlikely to bring down the entire structure. Thus managers are tempted to ignore or postpone aspects of TPM that they perceive as difficult, expensive or unpleasant.

Corporate culture is one such difficult and unpleasant issue. Suppose a company implements TPM without addressing their negative corporate culture. The improvement in operator attitudes in figure 9 is not realized or is negated by the overwhelmingly unpleasant culture. This cancels out three of the most important reinforcing loops and will seriously limit TPM's gains.

Benefit Growth

The Parthenon model (subtly) implies that the benefit growth is more or less linear and depends on how well each component (pillar) is implemented and when it is implemented. It would lead us to imagine that two stout columns are equivalent to five skinny columns. This may or may not be more or less true, depending on many factors in the individual situation.

The Parthenon model also implies that once a "pillar" is in place, no further construction is required; Do thisà get that; a linear relationship.

The dynamic model, in contrast, emphasizes the feedback loops that often lead to exponential growth. It also shows, more clearly, relationships between various aspects. It implies the very complex and (often) unpredictable behavior of dynamic systems.

Limits of The Dynamic Model

The dynamic model of figure 9 also has limitations. It is not intended to replace the Parthenon model but, rather, to supplement it.

One difficulty with the dynamic model is that it gives few hints about the tasks or techniques required for implementation. With the Parthenon model we can ask, for example, "What do we have to do to integrate Maintenance and Quality?" The answers lead to specific tasks and tools for accomplishing those tasks.

In reality, both models are necessary and there are undoubtedly other models or variations that would also be helpful. It is like observing sunsets. A sunset looks very different from a beach, from a mountain valley, the desert, the arctic or from an aircraft. Each perspective is different and each has value.

TPM and the Larger Lean System

While figure 9 attempts to show the dynamics of TPM within the maintenance system, figure 10 illustrates some of the interactions between TPM elements (pillars) and elements of the larger Lean system.

Workcells, for example, are an important element of Lean. Workcells encourage people to function as a team and teams make the cells function more efficiently. Workcells also improve quality and productivity. Workcells and teams are a natural fit with Autonomous Maintenance--the teams maintain the equipment and Autonomous Maintenance gives the teams greater control, which provides motivation. Workcells and Quality Integration are also a natural fit--the same people responsible for quality are also responsible for maintenance.

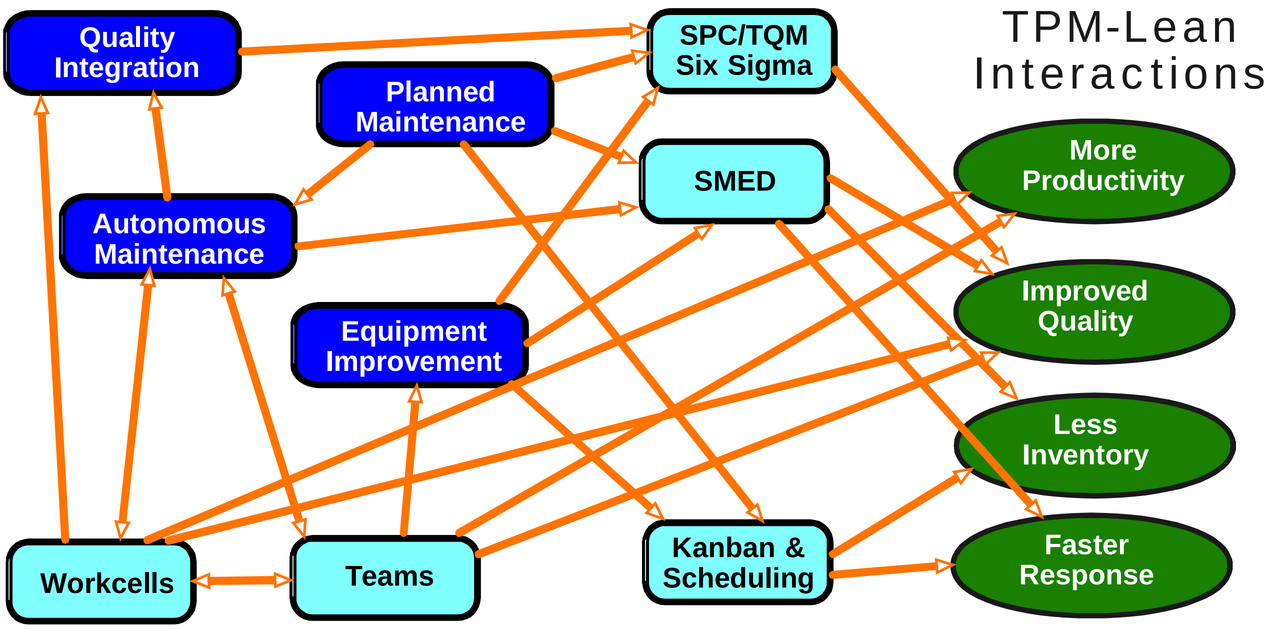
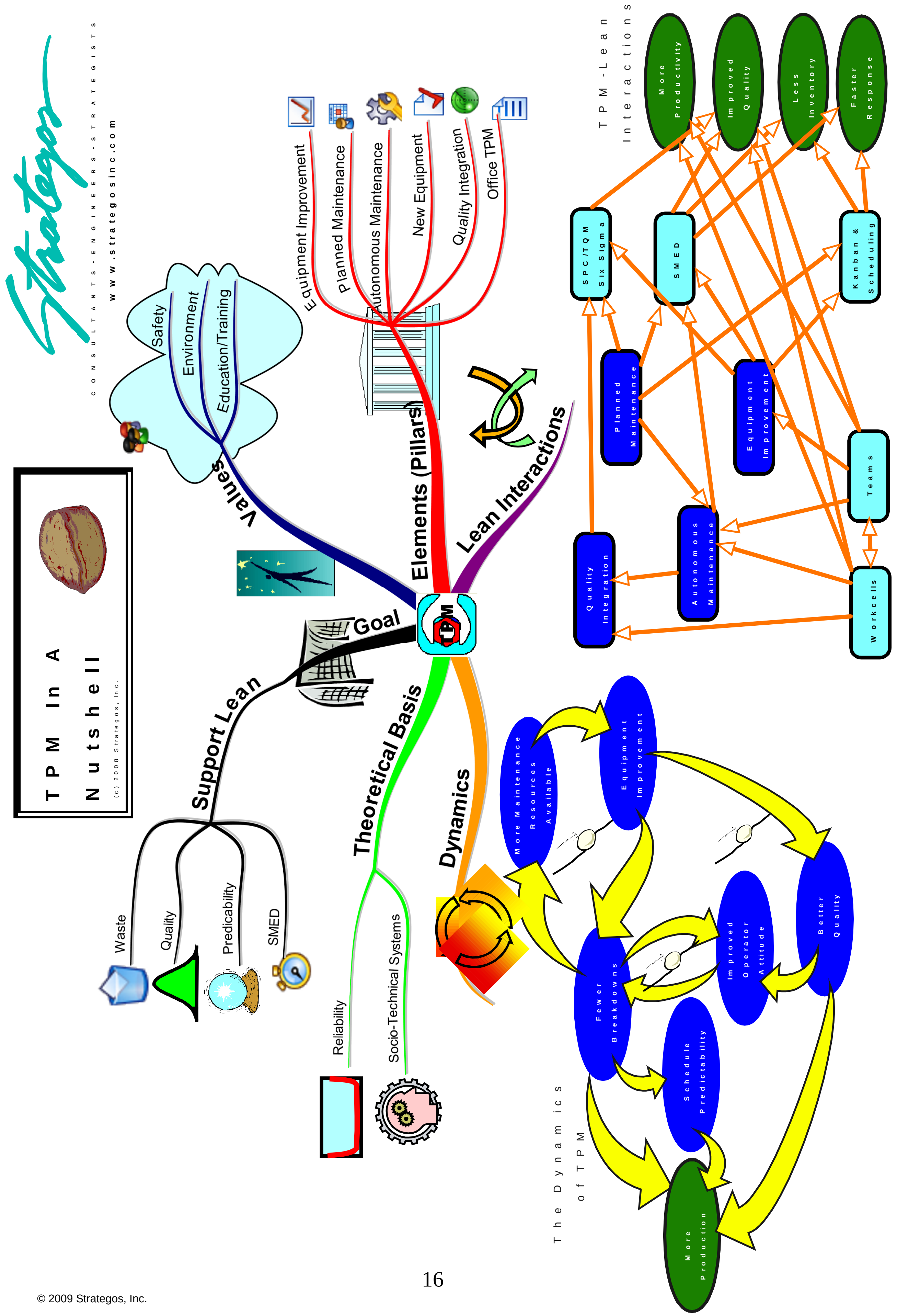


Figure 9 TPM & Lean Interactions

Many, many more such interactions exist. It is impossible to show them all and show them accurately on a computer monitor.

TPM In A Nutshell

Like much in Lean, TPM is a simple yet complex and subtle thing. This is partly because of the dynamic effects within TPM and interactions with other lean elements. In this article, we have only touched on a few basics. Our graphic summary, "TPM In A Nutshell" attempts to depict TPM in various aspects.



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Values
Safety
Environment
Education/Training
Elements (Pillars)
Equipment Improvement
Planned Maintenance
Autonomous Maintenance
New Equipment
Quality Integration
Office TPM
Lean Interactions
Goal
Support Lean
Waste
Quality
Predicability
SMED
Theoretical Basis
Reliability
Socio-Technical Systems
Dynamics
TPM-Lean Interactions
More Productivity
Improved Quality
Less Inventory
Faster Response
SPC/TQM Six Sigma
SMED
Kanban & Scheduling
Planned Maintenance
Equipment Improvement
Teams
Quality Integration
Autonomous Maintenance
Workcells
The Dynamics of TPM
More Maintenance Resources Available
Equipment Improvement
Better Quality
Improved Operator Attitude
Fewer Breakdowns
Schedule Predictability
More Production