Maintenance Best Practices for Outstanding Equipment Reliability and Maintenance Results

Maintenance Planning and Scheduling Day 1 Training Course Slides with Complete Explanations

from the

Maintenance Planning and Scheduling for World Class Reliability and Maintenance Performance 3-Day Training Course
The Maintenance Planning and Scheduling for World Class Reliability and Maintenance Performance Training Course Textbook 1

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1. Introduction

Maintenance is a huge profit centre when it is done correctly. It can make as much money for an industrial company as the operations group tasked to make the company’s products. But you have to do maintenance in a certain way. There is a best practice way to do maintenance planning and scheduling that guides companies and their maintenance crews to world class performance. I will tell you what you need to know to do world class maintenance planning and scheduling for outstanding reliability in this book and continue it throughout the course.

Managing limited resources so things are done on time for the least effort and cost is a must do requirement to become a world class maintenance organisation. Making work go smoothly, to budget and to schedule is vital in every maintenance activity. Maintenance Planning and Scheduling is a key component in delivering maintenance services effectively and efficiently.

After leaving the maintenance manager roll in an industrial process chemical manufacturer in 2005 I started presenting maintenance planning and scheduling training courses around Australia and Asia. The course I present is designed and built from a business owner's point of view. Unlike other maintenance planning and scheduling trainers who teach you the mechanics of maintenance planning and scheduling, I also teach you how to make vast sums money from maintenance through its proper preparation, organisation and delivery.

Maintenance done as explained in this book is not a cost. Great maintenance is a ‘rainmaker’ of moneys now lost to waste, catastrophe and misunderstanding. Maintenance planning and scheduling for reliability helps to double operating profit in the average industrial company.

Doing maintenance planning and scheduling is important. But the incredible difference to a company comes from what is done when you do the planning. The secret is knowing how to plan and prepare maintenance work so that it creates world class reliability. With world class reliability comes magnificent operational performance, and more operating profits than you can imagine. World class maintenance practices can double your margin and sustain it thereafter.

We will work our way through the three days of my ‘maintenance planning and scheduling for high reliability and maintenance performance’ training course. Just for fun I have woven a story though the book about Joe, the wise, old maintenance planner soon to retire, who is tasked with his last duty of training young Ted to take over his job.

First we will explain the business of maintenance and how to make a lot of money from it (a lot of money). After that we will cover maintenance planning and the secrets of preparing work to go smoothly, safely, as planned and ensure that it produces outstanding reliability. Lastly we complete the book with scheduling maintenance work so that the planned work produces the uptime which drives operational performance to previously unimagined heights.

I hope you get some of the joy from reading this book that I had in writing it. As always, if you have questions please ask me and I will explain. My view of maintenance is vastly different to just about everyone else in industry. That does not make my views right, but they do make a lot of money for those companies that use them.

Mike Sondalini
www.lifetime-reliability.com
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2. The Business Of Maintenance

Welcome to Maintenance Planning and Scheduling Training from Lifetime Reliability Solutions of Perth, Western Australia. Slide by slide we will work our way through the first day of the Maintenance Planning and Scheduling for World Class Reliability and Maintenance Performance training course and explain the necessary steps and understandings of what maintenance does for a company when it is done brilliantly.

Day 1 of the course

The role of Maintenance in business and its foundation basics

This Maintenance Planning training course is a little different to many others. It has a story line that hopefully will entertain you as it teaches you. I wanted to make training fun for you to do, and for me to write. So I decided to make it into a story of how Ted (he’s imaginary) learnt to become a top-gun Maintenance Planner and Scheduler.

The content of the training is exactly what you would get if you did our 3-day training course. Again, the course is different from other companies courses because it is tailored from 30 years of real-life experience as a tradesman, professional engineer and Maintenance Manager. I wanted my course to contain the really important stuff that is absolutely critical to understand, which actually works and makes a real difference to your performance and results.

Ted’s story follows the content of the course. Each day’s content is different and builds on previous information. The first day introduces people to the big issues of plant and equipment maintenance and reliability. It covers the foundations of maintenance planning and scheduling so you can see the important role it plays in keeping an operation running at full capacity and efficiency. Day Two is all about planning maintenance. You will be introduced to its necessary systems, methods and practices. Day Three includes working with the backlog and scheduling maintenance work so it is done in the quickest time with the least interruption to production.
Throughout the course you will do activities that provide opportunity to learn and discuss numerous issues and perspectives to do with Maintenance Planning and Scheduling.

Old Joe knows his stuff. Many years ago he saw the power of maintenance done well. Pay attention to what he say. More importantly, do what he advises you to do.

Maintenance Planning and Scheduling exists because it gives value to those businesses that use physical assets, such as plant, equipment, machinery, facilities and infrastructure, in providing their product to paying customers. The value planning and scheduling contributes is by minimising the waste of time and resources so production can be maximized.

In most small operations the planning and scheduling function is usually the part of the role and duties of workplace supervision. It becomes part of a day’s work for the Team Leader, or a Workshop Supervisor. But that is a bad idea. Unfortunately the planning portion of planning and scheduling is dropped when time becomes tight. The urgent demands of the day always dominate the important work of planning the future. Shortly after planning stops the maintenance jobs start going wrong, and consequently the amount and cost of maintenance increases.

In larger operations planning and scheduling become the whole job of a person. In still larger enterprises the planning and scheduling are separated and designated persons do each job.

Ted is asked to become the Maintenance Planner

Usually a person from the maintenance crew is asked to move into maintenance planning. Often it is a person who knows the plant and equipment well. The thinking behind the selection is that this person will know what to do in the planner’s roll because they are so experienced with the machinery. But planning has got nothing to do with how skilled one is with their hands when working on machines. Planning is about being methodical, disciplined, forward thinking and an
excellent organiser. If you are not strong in all those four requirements, then get exposure and experience in the weak areas so that you become more aware and able in doing them well.

Hey Joe, what did you tell Bill about me becoming a Planner?
I like what you do Joe, but I don’t know if I will ever be as good as you.

No problems Ted, you’ll be fine.
You’ve got three months to learn. Spend the first month it with me and I’ll walk you through it all. Then practice the job while I am still here. Now grab a seat and let’s start.

First you need to know what maintenance really is. I know you are a maintainer, but there is more to maintenance than fixing equipment.

Okay, what comes first.

Ted begins to learn about Maintenance

The best training is hands-on training. Do a thing until you do it correctly, and you will learn it faster and more thoroughly than reading or hearing about it. Classroom training helps you to get new ideas and new knowledge, but only the practical use of that knowledge will make it your own and bring you the benefits that you want.

To be good, really good, at a job, any job, you have to know everything about it. Things like—why it is done that way, what was its history, what works and what causes problems, how to fix the problems if they appear.

When you become expert everything is easy. But that takes exposure to situations along with discovering the best way to handle them. It requires that you learn all that you can from other people who do it well and from what is written by others about what you want to be good at.

I remember talking with a guy that I had worked with for years and he surprised me by saying he was a competition rifle shooter. When he talked to me about his hobby, his passion for target shooting welled-up from him. He said that to be a good competition shooter you had to assemble your own bullets. Those brought from the shop are to variable in performance.

He described how he measured the gunpowder into the cartridge, it had to be just the right weight to get the right trajectory. Not enough and the bullet went low, too much and the rifle kicked high. He told me how the bullet tumbled its way to the target and as it rolled end over end any wind would cause it to stray from target. He said how terribly important it was to adjust the sighting for the strength of the crosswind blowing. He described with delight how he lined-up the target and virtually ‘coached’ the bullet to the bullseye. He knew everything there was to know about his sport and the requirements to master it. He was an expert marksman.
You will need the same passion and dedication to become a ‘top-gun’ Maintenance Planner and Scheduler.

**Today’s Best Practice Maintenance Methodology**

(still misses the target!)

Maintenance methodology today has progressed to the approach shown in the slide. From the plant and process design the equipment criticality to the operation is identified. When doing the equipment criticality we identify the way equipment can fail and the risk a failure has on the business. Then we put in place appropriate methods and techniques to either prevent failure, or minimize its consequences. Suitable maintenance strategies are selected to provide the required availability for the plant and equipment. These strategies become the maintenance plans, resources and activities that are done to produce the desired uptime.

All this requires planning, coordination and cooperation between people in the operation in order to make sure maximum quality production is made, while also keeping machinery in top working order so that a quality product can be safely and surely produced.

This balance between production and production capability is an always a moving requirement that is actively managed by the people in the organisation through the use of a quality management systems and its processes. Maintenance planning and scheduling is a quality system process.

Unfortunately, even after more than two centuries of development, today’s maintenance management does not work very well. I can say that because production equipment put through the methodology shown in the slide continues to fail. If that maintenance methodology did work there would be zero failures. Even after more than two hundred years there is still something vital missing in our understanding and practice of doing maintenance. Without the missing ingredients we can never taste the success of getting zero failures. But there fair better answers. I can say that because in the world class companies their maintenance delivers zero failures.
The 6 Purposes of Maintenance Planning

The job of maintenance is to provide reliable plant for least operating cost – we don’t just fix equipment, … we improve it!

Maintenance has a greater purpose than simply looking after plant and machinery. If that was all that was necessary then maintainers would only ever fix equipment and do servicing. In today’s competitive world, maintenance has grown into the need to manage plant and equipment over the operating life of a business’ asset. It is seen as a subset of Asset Management, which is the management of physical assets over the whole life cycle to optimize operating profit.

There are at least six key factors required of maintenance to achieve its purpose of helping to get optimal operating performance. These are to reduce operating risk, avoid plant failures, provide reliable equipment, achieve least operating costs, eliminate defects in operating plant and maximise production.

In order to achieve these all people in engineering, operations and maintenance need great discipline, integration and cooperation. There needs to be an active partnership of equals between these three groups where the needs and concerns of each is listened to and integrated into the work.
What Makes a Productive Equipment Life?

When you make plant more reliable you work on the ‘capacity’ part of the Unit Cost equation. As a result you drive down the cost of your product because the plant is available to work at full capacity for longer. So you make more product in the same time for less cost.

Maintenance Planning and Scheduling add value here

Well performing businesses return their investments and generate good profits. The profitability from plant and equipment depends on the difference between how much it costs to operate and produce a product from them, and the selling price of the product. Equipment that runs without failure, at high capacity and product quality, with good efficiency and little waste will produce higher Return on Investment (ROI).

To achieve this ideal it is first necessary to have selected well-designed equipment suited to the task and situation, properly installed to high standards, run within design limits and cared for to the standards that retain design performance. Finally we continually improve the equipment as we learn more about it and we master its operating conditions. If any of the five foundation requirements are missing you will have problem plant.

The successful operations work hard to sustain a high capacity from their plant AND for low costs. This means they make a quality product, with a low unit cost that they can sell below competitor's prices, and so win greater market share, while still having good profits.
The Life Cycle of Plant and Equipment

The plant and equipment used in an enterprise have a life cycle. It starts with the recognition of an opportunity, then progresses to feasibility and approval. If the idea is found worthwhile a full design is developed, plant and machinery are purchased, installed, and put into operation. The vast majority of the life cycle is the operation phase, and this continues until the plant and equipment are eventually decommissioned and disposed of.

A business is started in the expectation that the investment made to get into operation will return a profit within a specified time. The profit is only generated during the operating phase of the life cycle. The more profitable the operation, the sooner the investment is returned, and the sooner an unencumbered income stream is created. If we want to maximize operating profit we must have costs no greater than those expected when the investment decision was made while keep the operation performing at the throughput approved.

One of those costs is the repairs and maintenance of the plant and equipment. When maintenance costs rise above forecast people start getting worried.
When Operating Costs are Committed

This Figure\(^1\) shows when plant operating costs are committed during the life cycle of an operation. It indicates that up to 95% of operating costs are predicated, or fixed-in-place, during the capital selection and design phase. By the time a plant goes into operation there is little that the people operating and maintaining the plant can do to change operating costs.

During the operating phase of the life cycle the focus is to minimise operating costs to the very lowest levels achievable with the plant and equipment supplied. The Maintenance Planner contributes to the important goal of least-cost-of-operation by making sure that the use of people and resources is minimised and they are used wisely for the greatest benefit of the enterprise. Hence the primary purpose of maintenance planning is “to gain the greatest work utilization from the maintenance mechanics”, i.e. to maximise ‘tool time’.

The costs committed curve has one more important message. It advises us that operating costs are the result of decisions made during feasibility, design and construction. If you want low cost operation you must make decisions that later bring you low operating costs when selecting production and operating processes and buying their associated plant and equipment. You design low cost operation into a business by the choices you make during the feasibility and project phases. When you buy the plant and equipment for a business you also buy whatever it costs to operate and maintain it. Once you get equipment that is expensive to keep and use there is nothing you can do about it except to replace it with better equipment.

Do not rush your projects into development. You have one chance to get it right for the rest of an operation’s life. Take 10% longer in the project phase to do the research and life cycle cost comparisons to identify low operating cost equipment. Spend 10% more on capital to buy lower maintenance and low operating cost plant and equipment. It will return you a fortune. DuPont have learnt that they need to design a plant to 65% of final design if they want to get costs to

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within ± 10% accuracy. In DuPont projects are never approved until 65% of the design is completed. They know that it needs that level of detail if you want to know the full costs.

The Asset Management ‘Journey’ Model

There is a ‘big picture’ to see and understand if you want to be successful in maintenance planning and scheduling. This vision is called ‘The Journey’ to operational excellence. If we want to create outstanding businesses that satisfy all stakeholders, including ourselves, we will need a business that works like a well-designed, well operated and properly cared-for machine. The operation must run reliably, at full capacity, with no problems. To get to that point needs a business that is fully coordinated and integrated so that everyone helps everyone else perform at world-class levels.

The conceptual operating model in the slide comes from work done by DuPont in the 1980s and 90’s. It is known as the ‘Stable Operating Domain Model’ and is espoused by many people in the physical asset management community as the ideal model to use. It supposedly shows the stages that an industrial business must pass through to achieve operational excellence. Most businesses start at the reactive stage where they wait for things to go wrong. The better businesses move to the planned stage where they are organised to minimise operating failures. The good businesses change to become a reliable organization that prevents problems from starting. The ultimate businesses look for perfection, where all that they do supports ideal performance.

You can take DuPont’s model for developing operating excellence as our own, a lot of people have done so. Supposedly it says what must be done to travel the journey to world-class operating performance. It is used by many companies to justify the effort of getting maintenance planning and scheduling working well. In the model the planned state is the first step on the journey. But there is a serious flaw with the model—it is not possible to replicate it with

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\(^2\) Hutnic Robert (Bob), Maximizing Operational Efficiency Seminar, E. I. du Pont de Nemours and Company, 2004
confidence. Very few who use this model actually make the journey to world class. No one really understands how to use the model and make it work. The model must have flaws if it cannot be replicated in every company across the world.

It is because a stable domain can only be established when a company and its people have the capability, beliefs and values that each state needs. With the power of hindsight it can be seen that DuPont set-in-place new, higher benchmarks and work standards and made it clear that their people needed to learn to become better at their work in order to make the journey to excellence. They brought their people to higher levels of understanding, expertise and skill. Once the people had the capability and willingness to change they made their company better. That need for greater engineering education, for understanding and integrating systems and processes, and for the achievement of excellence is shown by the arrow pointing along the path of ‘the journey’.

The Best Practice ‘Journey’ to Reliability

Here is an alternate view of the ‘journey’ to best-in-class. This ‘map’ makes it clear what ‘steps’ to take on the journey to operational excellence. It comes from my book Plant and Equipment Wellness available from the Engineers Australia bookstore. It shows the activities, practices and methodologies to bring into your operation at the various stages of the journey. In the end you must integrate across the company and throughout the life cycle and work in ways that will deliver excellence in all activities and decisions.
Basic Maintenance Management Process
(The best also imbed quality management into the maintenance processes.)

These are the basic components of a maintenance management process. The six steps will get work done and equipment maintained. Though not very well. Most industrial companies do these things every day, but they do not get the great benefits possible from maintenance because its activities are seen as not being a core part of the company’s success. Instead of integrating the learning gained from looking into why their machines fail, and changing their other business processes to correct the problems they cause, most companies only focus on getting product out, totally missing the opportunity of improving their life cycle and operating processes to prevent the problems in the first place.

What all companies need is a quality management system to take learning throughout the business and make things better everywhere.
Strategic Business Importance of Using Maintenance to Deliver Reliability

The Best Companies Differ Substantially From The Average!

The best give greater focus to the denominator of the unit cost equation (while they still watch costs). They apply best quality practices to assure maximum capacity, most efficiently, without incremental capital investment and their unit costs come down as a consequence! The typical company gives greater focus to cost cutting, without changing the basic processes which cause the high costs!

What would you do if you were Company ‘C’ or ‘B’ and ‘A’ decided to grow market share?

Maintenance maximises production capacity by keeping equipment available in a condition to make quality product while running at full throughput.

The Japanese say that a new machine is in the worst condition that it should ever be in.

This concept is one that Ron Moore of the RM Group uses to explain why the best businesses perform so well. It shows a competitive market place of three companies and their relative market share and product cost. Each company remains in business for different reasons. Company C has high costs, but retains customers because it does special requirements for them. Company A is the low cost producer and sells to customers based on least price. Company B is in a difficult position because it neither provides for special needs, nor has the best price. It exists because Company A cannot supply the total demand of the market.

Selling products does not make money for a business. The business only makes money if it can sell its products for a profit. If you have to sell at a price because competitors are selling at that prices, then you may be selling at or below cost. The business won’t last long if it sells its products for less than it can make them.

The real message in the slide is that a company needs to focus on achieving least unit cost of production if it wants to win the marketplace. The equation for Unit Cost shows this can be done by either reducing the cost of production, or by increasing the capacity to make more product for the same cost of production. However, those companies that focus on cost reduction risk compromising their product quality and marketplace reputation. They will buy cheaper raw materials, try and use incompetent staff, slash maintenance, and the like.

But those companies that work to increase their plant capacity achieve lower product cost because they make more product for the same cost of production. They increase equipment reliability, they increase the skills and knowledge of their employees, they use risk reduction practices, like Accuracy Controlled Enterprise 3T (Target-Tolerance-Test) procedures, throughout their business processes.
Joe, our hour is up.

Yea, … sure ….

Humm … what’s that got to do with maintenance?

Joe sets Ted a trick question.

Okay Ted, see you the same time tomorrow. … But think about this between now and then: *How does the business make its money?*

Hi Ted.

So then … *How does the business make its money?*

Sales is part of the answer, but not the most important part. Sit with me at the table and let me explain it to you with this diagram.

Hi Joe.

I thought about it last night, but I couldn’t think of any answer other than - ‘we sell the products we make’.

The next day …

Joe is on the right track. Selling product is important, but you need to make sure it is for a price that makes money so the company can stay in business and pay its people, buy its raw materials, care for its infrastructure, and pay its running costs and its taxes.
The Purpose of Business

The Figure is a simple accounting model of a business that every new accountancy student is shown. When a business operates it expends fixed and variable costs to make the product it sells. Fixed costs are those outgoings you must always pay regardless of whether the plant is running or not, such as wages and salaries, rental agreements, lease agreements, land rates and taxes, etc. Variable costs are the moneys you pay because you run your plant and equipment, things like water, power, fuel, raw materials, contracted services, etc.

From doing business a profit is made that keeps it trading. The variable costs and fixed costs makeup the total cost. If the product is sold for more than the total cost a profit is made.

Two fundamental accounting equations derive from the model. The first equation explains how businesses make money.

\[
\text{Profit} (\$) = \text{Revenue} (\$) - \text{Total Costs} (\$) \quad \text{Eq. 1}
\]

When the costs are less than the revenue the business is profitable. The next equation explains where expenses and costs arise.

\[
\text{Total Costs} (\$) = \text{Fixed Costs} (\$) + \text{Variable Costs} (\$) \quad \text{Eq. 2}
\]
Maintenance is Cheap; Repairs are Expensive

Profit ($) = Revenue ($) - Total Costs ($)  
Total Costs ($) = Fixed Costs ($) + Variable Costs ($)  

You Maintain right and Operate right so that the right practices prevent repairs!

Maintenance costs also comprises a fixed cost component for doing Preventive Maintenance (PM) and Predictive Maintenance (PdM) and a variable cost component for doing repairs after equipment fails. If plant and equipment failures are excessive the variable costs rise but cannot be passed onto customers. Hence too many repairs due to failures takes profit from the business. If not contained, the failures will make the business unprofitable.

But maintenance alone cannot create reliability without the plant also being operated in the right ways that do not cause breakdowns. Operational excellence needs both Production to run the plant well and Maintenance to keep the plant in good health (and as we saw in the life cycle cost curve—operational excellence needs Engineering/Projects to chose reliable equipment in the first place).

Modern maintenance and reliability strategy is to use fixed cost maintenance methods to prevent failures and so limit the variable maintenance costs. This is best achieved by identifying and applying proactive maintenance to prevent failures from happening in the first place.

The very best maintenance operations know that their maintenance costs will be within ± 1% to 2% of budget year after year because they have set up the right maintenance tasks that create sure availability and made them the normal, fixed maintenance cost activities which their people do. They use fixed cost work to prevent profit threatening variable cost breakdowns.
Impact of Defects and Failures

Once the equipment fails, new costs and losses start appearing.

The failure incident stops the operation at time $t_1$ and. A number of unfortunate things immediately happen to the business. Future profits are lost because product that should be made to sell is not (though stock is sold until gone, which is why buffer stock is often carried by business that suffer production failures). The fixed costs continue accumulating but are now wasted because there is no product produced. Usually operation department workers do other duties to fill-in time. Some variable costs fall, whereas others, like maintenance and subcontracted services, can rise suddenly in response to the incident. Other variable costs, like storage of raw material and contracted transport services, wait in expectation that the equipment will be back in operation quickly. These too are wasted because they are no longer involved in making saleable product. The losses and wastes continue until the plant is back in operation at time $t_2$. Some costs can continue for months. The costs can be many times the profit that would have been made in the same time period.

Production need to recognise that the cost of failure is a separate waste that needs to be controlled and reduced. If a failure happens in a business that prevents production, the costs escalate and profits stop. Fixed costs are wasted and variable costs rise as rectification is undertaken. To these costs are added all the other costs that are spent or accrue due to the incident. A more accurate cost equation that all businesses should use is shown in Equation 3.

$$\text{Total Costs ($)} = \text{Productive Fixed Costs ($)} + \text{Productive Variable Costs ($)} + \text{Costs of Loss ($)}$$  
$$\text{Eq. 3}$$

Equation 3 is powerful because it recognises the presence of losses and waste in a business. From this equation is derived another that explains how businesses can lose a great deal of money.

$$\text{Cost of Loss ($/Yr)} = \text{Frequency of Loss Occurrence (/Yr)} \times \text{Cost of Loss Occurrence ($)}$$  
$$\text{Eq. 4}$$
Equation 4 tells us that money is lost every time there is a failure. The equation is a power law, which means failure costs are not linear and while one incident may lose a few dollars, another can total immense sums of money.

The cross-hatched areas in the Figure show that when a failure happens the cost to the business is lost future profits, plus wasted fixed costs, plus wasted variable costs, plus the added variable costs needed to get the operation back in production. The cost impact for repair from a severe outage (the dotted outline in the Figure) can be many times the profit from the same period of production. Not shown are the many consequential and opportunity costs that extend into the future and are forfeited because of the failure.

When equipment fails, operators stop normal duties that make money and start doing duties that cost money. The production supervisors and operators, the maintenance supervisors, planners, purchasers and repairmen spend time and money addressing the stoppage. Meetings occur, overtime is ordered, subcontractors are hired, the engineers investigate, and necessary parts and spares are purchased to get back in operation. Instead of the variable costs being a proportion of production, as intended, they rise and take on a life of their own in response to the failure. Whatever money is required to repair the failure and return to production will be spent. Losses grow proportionally bigger the longer the repair takes, or the more expensive and destructive it is.

If it escalates managers from several departments get involved – production, maintenance, sales, despatch, finance – wanting to know about the stoppage and when it will be addressed. Formal meetings happen in meeting rooms and impromptu meetings occur in corridors. Specialists may be hired. Customers may invoke liability clauses when they do not get deliveries. Word can spread that the company does not meet its schedules and future business is lost through bad reputation. Rushed work-arounds develop that put people at higher risk of injury. Items and men move about wastefully, materials and equipment rush here-and-there in an effort to get production going. Time and money better used on business-building activities falls into the ‘failure black hole’. On and upward the costs build, and the company’s resources and people are wasted. The reactive costs and the ensuing wastes start immediately upon failure and continue until the last cent on the final invoice is paid. Some consequential costs may continue for years after. The company pays for all of this from its profits, and reflects to the whole world as poor financial performance.

After a failure, it is common to work additional overtime to make-up for lost production in order to fill orders and replenish stocks. But that time should have been for new production. Instead, it is time spent catching-up on production lost because of the failure. Once time is lost on a failure, the production and profit from that time are also lost. It gets much worse if there are many failures.

What is not well understood, are the massive surge of costs and accumulation of losses that occur throughout a business when plant and equipment fail. The table below lists 66 business-wide defect and failure costs that can arise from a forced stoppage. Most of these costs are hidden from view by the cost accounting practices in use today. Normal financial accounting practices do not recognised these costs for what they are; unnecessary waste and loss. Because many of the costs of failure are unseen, little is done to stop them, yet they continually rob commerce and industry of vast profits.

Company managers hardly ever cost failures fully and correctly. They do not identify all the costs that result because of the failure. The true cost of failure to a business is far bigger that simply the time, resources and money that goes into the repair. Failures and stoppages are the
number one enemy in running a profitable operation. They have a cumulative impact on the operation’s financial performance. With too many failures or downtime incidents, a business becomes unprofitable. The money spent to fix failures, and to pay for the wasted costs, leaves only poor operating profits behind.

Defect and Failure Total (DaFT)
Costs and Losses go Company-wide

<table>
<thead>
<tr>
<th>Labour: direct and indirect</th>
<th>Materials</th>
<th>New insurance, spares, buildings and storage, assets write-off</th>
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<tbody>
<tr>
<td>operators</td>
<td>replacement parts</td>
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<td>repairs</td>
<td>fabricated parts</td>
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<td>supervisory</td>
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<td>management</td>
<td>welding consumables</td>
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<td>overtime penalty rates</td>
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<td>replacement production</td>
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<td>clean-up</td>
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<td>reprocessing</td>
<td>design changes</td>
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<td>handover/returned-back</td>
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<td>lost production</td>
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<td>lost spot sales</td>
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<td>off-site storage</td>
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<td>environmental rectification</td>
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<td>emergency hire</td>
<td>OEM work</td>
<td></td>
</tr>
<tr>
<td>sub-contractors</td>
<td>energy waste</td>
<td></td>
</tr>
<tr>
<td>travelling</td>
<td>shutdown</td>
<td></td>
</tr>
<tr>
<td>consultants</td>
<td>start-up</td>
<td></td>
</tr>
<tr>
<td>utility repairs</td>
<td>inefficiencies</td>
<td></td>
</tr>
<tr>
<td>temporary accommodation</td>
<td>emergency hire</td>
<td></td>
</tr>
<tr>
<td>Capital</td>
<td>damaged items</td>
<td></td>
</tr>
<tr>
<td></td>
<td>replacement equipment</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It’s unbelievable how much money is wasted all over the business with each failure. The one I like is the time lost matching invoices against purchase orders that did not need to be raised, but for the failure! The ‘lost life value’ of parts is expensive too.

A failure takes money and resources from throughout a company. The moneys from a failure are lost in Administration, in Finance, in Operations, in Maintenance, in Service, in Supply, in Delivery and even in Sales. There will be operating and maintenance costs for rectification and restitution, for manpower, for subcontracted services, for parts, for urgent overtime, for the use of utilities, for the use of buildings and for many other requirements not needed but for the failure. The Executive incurs costs when senior managers get involved in reviewing the failure. The Information Technology group may be involved in extracting data from computer systems and replacing hardware. The finance people will process purchase orders and invoices and make payments. Engineering will incur costs if their resources are used. Supply and Despatch will be required to handle more purchases and deliveries. Sales will contact customers to apologise for delays and make alternate arrangements. Thus the failure surges through the departments of an organisation.

Failures cause direct and obvious losses but there are also hidden, unnoticed costs. No one recognises the money spent on building lights and office air conditioning that would normally have been off, but are running while people work overtime to fix an equipment breakdown. No one counts the energy lost from cooling equipment down to be worked-on and the energy spent reheating it back to operating temperature, those products scrapped or reworked, the cost to prepare equipment so it can be safely worked-on, or the cost of replacement raw materials for that wasted, along with many other needless requirements that arose only because of the failure. Though these costs are hidden from casual observation, they exist and strip fortunes out of company coffers, and no one is the wiser.
Still another loss category is opportunity costs, such as the wages of people waiting to work on idle machines, costs for other stopped production machinery standing idle, lost profits on lost sales, penalties paid because product is not available, people unable to work through injury, along with many other opportunity costs.

Failure Costs Surge thru the Company

Every department in the business gets hit from the ‘failure cost surge’.

The Figure represents the cost surge that rips through a company with every equipment failure. The total impact of equipment failure is hidden amongst the many cost centres used in a business. For a failure incident to be fully and truly costed it is necessary to collect the numerous costs that surge throughout the operation into a single cost centre. It is not until all the costs, wastes and losses of failure are traced in detail throughout the business that the complete and true cost of failure is known. This costing process is known as Defect and Failure Total Costs (DAFT Costs) analysis.

The total impact of equipment failure is hidden amongst the many cost centres used in a business. For a failure incident to be fully and truly costed it is necessary to collect the numerous costs that surge throughout the operation into a single cost centre. It is not until all the costs, wastes and losses of failure are traced in detail throughout the business that the complete and true cost is known. This is done by following a failure throughout the business using the list of DAFT Costs in a spreadsheet similar to those shown in the next slide.

**Instantaneous Costs of Failure**

These lost and wasted moneys are the ‘Instantaneous Costs of Failure’. The moment a failure incident occurs the cost to fix it is committed. It may take some time to rectify the problem, but the requirement to spend arose at the instance of the failure. How much that cost will eventually be is unknown, but there is no alternative and the money must be spent to get back into production. The moneys spent to fix the problem, the lost income from no production, the
payment of unproductive labour, the loss from wastes, the handling of the company-wide disruptions and the loss of business income is gone forever. All of it is totally unnecessary, because the failure did not need to happen.

The total organisation-wide Instantaneous Costs of Failure are not usually considered. Few companies fully investigate the huge consequential costs they incur with every failure incident. Many Instantaneous Costs of Failure are never recognised. Businesses miss the true magnitude of the moneys lost to them. Few companies would cost the time spent by the accounts clerk in matching invoices to the purchase orders raised because of a failure. But the clerk would not do the work if there had been no failure. Their time and expense was due only to the failure. The same logic applies for all failure costs – if there had been no failure there would have been no costs and no waste. Prevent failures and the money stays in the business as profit.

It is not important to know how many times a failure incident happens to justify calculating its Instantaneous Cost of Failure. It is only important to ask what would be the cost if it did happen. The cost of ‘instantaneous losses’ from a failure incident can be calculated in a spreadsheet. It means tracing all the departments and people affected by an incident, identifying all the expenditures and costs incurred throughout the company, determining the fixed and variable costs wasted, discovering the consequential costs, finding-out the profit from sales lost and including any recognised lost opportunities due to the failure and tallying them all up. It astounds people when they see how much money was lost and profit destroyed by one small production failure.

The direct costs of failure, the costs of hidden waste, the opportunity costs and all other losses caused by a failure are additional expenses to the normal running costs of an operation. They were bankable profits now turned into losses. The 66 costs of failure listed reflect many of them. But there may be other costs, specific to an organisation, additional to those listed and they also would need to be identified and recorded.
In order to focus on preventing failures it is necessary to have a means to find the total costs of a failure and identify their full impact on an operation. Vast sums of money can be lost when things go wrong. A few large catastrophes close together in time, or many smaller problems occurring regularly, will destroy an organisation’s profitability. Too many defects, errors and failures send a company bankrupt. Typically, failures get quick repair and then work continues as usual. If anyone enquires on the failure cost, the number usually quoted is for parts and labour to fix it. They do not ask for the true impact throughout the organisation and the total value of lost productivity. But a business pays for every loss from its profits. The importance of knowing true failure cost is to know its full impact on profitability and then act to prevent it.

Collating all costs associated with a failure requires the development of a list of all possible cost categories, sub-categories and sub-sub-categories to identify every charge, fee, penalty, payment and loss. The potential number of cost allocations is numerous. Each cost category and sub-category may receive several charges. The analysis needs to capture all of them.

The worked example of a centrifugal pump failure in the following Table identifies what it truly costs. In this failure the inboard shaft bearing has collapsed. This bearing is on a 50 mm (2 inch) shaft. It is a tapered roller bearing that can be brought straight-off the shelf from a bearing supply. A common enough failure and one that most people in industry would not be greatly bothered by. It would simply be fixed, and no more would be thought about it by anyone.

For the example the wages employees, including on-costs, are paid $40 per hour and the more senior people are on $60 per hour. The product costs $0.50 a litre to make and sells for $0.75 per litre. Throughput is 10,000 liters per hour. Electricity costs $0.10 per kW.Hr. All product made can be sold. The failure incident apparent costs are individually tallied and recorded.
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Fax: +61 8 9457 8642  
Email: info@lifetime-reliability.com  
Website: www.lifetime-reliability.com

<table>
<thead>
<tr>
<th>Action No.</th>
<th>Description</th>
<th>Time (minutes)</th>
<th>Labour Cost</th>
<th>Materials Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>First the pump stops and there is no product flow.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>The process stops.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>The control room sends an operator to look.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Operator looks over the pump and reports back.</td>
<td>10</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Control room contacts Maintenance.</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Maintenance sends out a craftsman.</td>
<td>15</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Craftsman diagnoses problem and tells control room.</td>
<td>10</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Control room decides what to do.</td>
<td>10</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Control room raises a work order for repair.</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Maintenance leader or Planner looks the job over and authorizes the work order.</td>
<td>30</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Maintenance leader or Planner writes out parts needed on a stores request.</td>
<td>15</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Storeman gathers spares parts together and puts them in pick-up area. (Bearings, gaskets, etc)</td>
<td>20</td>
<td>13</td>
<td>350</td>
</tr>
<tr>
<td>13</td>
<td>Maintenance leader delegates two men for the repair.</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Maintenance leader or Planner organizes a crane and crane driver to remove the pump.</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Repair men pick up the parts from store and return to the workshop.</td>
<td>10</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Repair men go to job site.</td>
<td>15</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Pump is electrically isolated and danger tagged out.</td>
<td>15</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Pump is physically isolated from the process and tagged.</td>
<td>30</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Operators drain-out the process fluid safely and wash down the pump.</td>
<td>30</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Repair men remove drive coupling, backing plate, unbolt bearing housing, prepare pump for removal of bearing housing.</td>
<td>90</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Crane lifts bearing housing onto a truck.</td>
<td>15</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Truck drives to the workshop.</td>
<td>5</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Bearing housing moved to work bench.</td>
<td>5</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Shaft seal is removed in good condition.</td>
<td>20</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Bearing housing stripped.</td>
<td>90</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>New bearings installed and shaft fitted back into housing.</td>
<td>120</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Mechanical seal put back on shaft.</td>
<td>20</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Backing plate and bearing housing put back on truck.</td>
<td>10</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Truck goes to back to job site.</td>
<td>5</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Crane and crane driver lift housing back into place.</td>
<td>20</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Repairmen reassemble pump and position the mechanical seal.</td>
<td>60</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Laser align pump.</td>
<td>60</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Isolation tags removed.</td>
<td>10</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Electrical isolation removed.</td>
<td>15</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Process liquid reintroduced into pump.</td>
<td>30</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>Pump operation tested by operators.</td>
<td>15</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Pump put back on-line by Control Room.</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>755</td>
<td>$970</td>
<td>$350</td>
</tr>
</tbody>
</table>

Table  Apparent Costs of a Pump Bearing Failure

The whole job took 12.6 hours at an apparent repair cost of $1,320. The downtime was clearly a disaster but the repair cost was not too bad. Another problem solved. But wait, all costs are not yet collected. There are still more costs to be accounted for as shown in the next Table.

<table>
<thead>
<tr>
<th>Action No.</th>
<th>Description</th>
<th>Time (minutes)</th>
<th>Labour Cost</th>
<th>Other Cost/Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>Control Room meets with Maintenance Leader.</td>
<td>10</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>Control Room meets with repairmen over isolation requirements.</td>
<td>10</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>Production Manager meets Maintenance Leader.</td>
<td>5</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>Production Manager meets Maintenance Manager.</td>
<td>5</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>Production morning meeting discussion takes 5 minutes with 10 people management and supervisory present.</td>
<td>5</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>
Table: Additional Costs of a Pump Bearing Failure

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Cost 1</th>
<th>Cost 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>44</td>
<td>Production Planner meets with Maintenance Planner</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>45</td>
<td>General Manager meets with Production Manager</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>46</td>
<td>Courier used to ferry inboard bearing as only one bearing was in stock.</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>47</td>
<td>Storeman raises special order for bearing.</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>48</td>
<td>Storeman raises special order for gaskets.</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>49</td>
<td>Storeman raised special order for stainless shims on pump alignment but has to buy minimum quantity.</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>50</td>
<td>Storeman raises order to replenish spare bearing and raises reorder minimum quantity to two bearings.</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>51</td>
<td>Storeman raises order to replenish isolation tags.</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>52</td>
<td>Crane driver worked over time.</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>53</td>
<td>Both repairmen worked overtime.</td>
<td>600</td>
<td>400</td>
</tr>
<tr>
<td>54</td>
<td>Extra charge to replace damaged/soiled clothing.</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>55</td>
<td>Lost 200 liters of product drained out of pump and piping.</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>56</td>
<td>Wash down water used 1000 liters.</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>57</td>
<td>Handling and treatment of waste product and water.</td>
<td>13.7</td>
<td>20</td>
</tr>
<tr>
<td>58</td>
<td>Pump start-up 75 kW motor electrical load usage.</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>59</td>
<td>13.7 hours of lost production at $2,500/hour profit.</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>60</td>
<td>Account clerk raises purchase orders, matches invoices; queries order details, files documents, does financial reports. Paper, inks, clips.</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>61</td>
<td>Storeman answer order queries.</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>62</td>
<td>Maintenance workshop 1000 watt lighting on for 10 hours.</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>63</td>
<td>Two operators standing about for 13 hours.</td>
<td>750</td>
<td>1000</td>
</tr>
<tr>
<td>64</td>
<td>Write incident notes for weekly/monthly reports.</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>65</td>
<td>Incident discussed at senior levels three more times.</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>66</td>
<td>Stocks of product run down during outage and production plan/schedule altered and new plan advised. Paper, inks, printing</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>67</td>
<td>Reschedule deliveries of other products to customers and inform transport/production people.</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>68</td>
<td>Ring customers to advise them of delivery changes.</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>69</td>
<td>Electricity for lighting and air conditioning used in offices and rooms during meetings/calls.</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>TOTAL OF EXTRA COSTS</td>
<td>$2,018</td>
<td>$32,905</td>
</tr>
</tbody>
</table>

The true cost of the pump failure was not $1,320; it was $36,243–20 times more. The apparent cost of the failure is miniscule in comparison to the total cost of its affect across the company. That is where profits go when failure happens; they are spent throughout the company handling the problems the failure has created and vanish on opportunities lost. Identifying total failure costs produces an instantaneous cost of failure many times greater than what seems apparent. Vast amounts of money and time are wasted and lost by an organisation when a failure happens. The bigger the failures, or the more frequent, the more resources and money that is lost. Potential profits are gone, wasted, and they can never be recouped.

The huge financial and time loss consequences of failure justify applying failure prevention methods. It is critical to a company’s profitability that failures are stopped. They will only be stopped when companies understand the magnitude of the losses, and introduce the systems, training and behaviours required to prevent them.
### Downtime and Failure Costing Spreadsheets

(With thanks to [www.BIN95.com](http://www.BIN95.com) for use of the spreadsheets)

<table>
<thead>
<tr>
<th><strong>EQUIPMENT</strong></th>
<th><strong>Production</strong></th>
<th><strong>Quality Control</strong></th>
<th><strong>Delivery</strong></th>
<th><strong>Engineering</strong></th>
<th><strong>Other Production related personnel</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance</td>
<td>Setup personnel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quality Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Production</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Engineering</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other Maintenance Support personnel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Management</td>
<td>Floor Supervisors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maintenance Manager</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Production Manager</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Engineering Manager</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>General Manager</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Administrative</td>
<td>Maintenance Secretary</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MIS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accounting</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Legal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost per Unit</td>
<td>Raw Material</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Direct Labour Input</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Indirect Labour Input</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Processing Costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Units per Hour</td>
<td>Rated Equipment Rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Waste Cost</td>
<td>Electrical (Eg: High torque motors)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set-up</td>
<td>Extra material, product/tool delivery</td>
<td></td>
<td></td>
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<td>Manpower (supervisory tool)</td>
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<tr>
<td>Percent Reduced Production</td>
<td>Parts per hour lost</td>
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<tr>
<td>Equipment Fatigue</td>
<td>High torque motor, heater elements</td>
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<td></td>
<td>Computer monitors, mechanical fatigue</td>
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<tr>
<td>Scrap produced</td>
<td>Is it recyclable, salvageable?</td>
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<tr>
<td>Quality</td>
<td>Inspection cost, Rework cost</td>
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<tr>
<td>Other Cost</td>
<td>Site specific start up cost factors</td>
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<tr>
<td>Bottleneck Losses</td>
<td>Cost per Time Unit</td>
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<tr>
<td>Downstream Equipment Stoppages</td>
<td>Cost per Time Unit</td>
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<td>Sales Lost</td>
<td>Cost per Time Unit</td>
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<tr>
<td>Curtained and Lost Life of Parts</td>
<td>The working life parts could have had</td>
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<tr>
<td>LABOUR</td>
<td>Labour Per Part / Labour Per Machine</td>
<td>Direct Labour Input</td>
<td></td>
<td>Direct QC labour related to downtime</td>
<td>First product inspections</td>
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<tr>
<td>DOWNTIME</td>
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<td>Curtailed Lives</td>
<td>Proportion of cost from past repairs that did not last a full life</td>
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<td>Lost Time</td>
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<td>Reduced</td>
<td>Capacity loss</td>
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<td></td>
<td>Maintenance time</td>
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<td>Scrap</td>
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<td>Band Aid</td>
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<tr>
<td>OEM</td>
<td>Time and material</td>
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<td>Expenses</td>
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<td>Downtime losses</td>
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<tr>
<td>Tooling</td>
<td>Tooling damage caused by Machine failure</td>
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<td></td>
<td>Machine failure caused by Tooling damage</td>
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<td>Parts &amp; Shipping</td>
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<tr>
<td>Cost of this occurrence</td>
<td>Associate cost to permanent fix done later</td>
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<td></td>
<td>Parts used for band-aid repair</td>
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<td>Amount of times band-aided till permanent fix, etc.</td>
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<tr>
<td>Percentage of all other Downtime Metrics</td>
<td>What percent of full speed, increased scrap, extra manpower, tool breakage, etc.</td>
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And clearly, repeated plant and equipment failures and stoppages totally destroy the profitability of an operation.

The Figure shows the effect of repeated failures on the operation of our model business. Repeated failures cause a business to bleed profit from ‘a death of many cuts’.

**Risk Rating with DAFT Costs**

Putting a believable value to a business risk consequence is important. Selecting risk mitigation without knowing the size of the risk being addressed sits uncomfortably with managers. They need a credible value for their financial investment modelling and analysis. Once the financial worth of a risk is known, management can make sound decisions regarding the appropriate action, or lack of action, required for the risk. DAFT Costing provides a believable and traceable financial value for managers to use because the values in the costing tables are drawn from the company’s own accounting systems. None of the costs are estimates; rather they are calculated from real details.

Having a real cost of failure permits a truer identification of the scale of a risk. With the cost consequence of a failure known accurately the only remaining uncertainty is the frequency of the event. Instead of having two uncertain variables in the risk equation – frequency and consequence – the potential for large errors are significantly reduced if the failure cost is certain. A manager is more confident in their decisions when they have a good appreciation of the full range of a risk that they have to address.
3. Understanding Operating Risks

**Benefits of Reducing Operating Risk**

Risk is the product of the likelihood that an event will happen and the cost if it does. Operating equipment risk is the size of the financial loss from an equipment failure during operation. It is calculated by substituting ‘loss’ in Equation 4 with ‘equipment failure’, as shown in Equation 5.

\[
\text{Operating Risk ($/Yr)} = \text{Chance (/Yr)} \times \text{Consequence ($)}
\]

The cost of failures during operation can be reduced in one of two ways. By reducing the consequence of failure and by reducing the chance of failure. In the top Figure on the slide the consequence of time loss has been reduced so that repairs are completed rapidly. As a result production is back in operation faster and so fewer profits are lost. The lower Figure represents reducing the chance of failure where fewer failures occur during the same period of time. This also reduces profit lost because less things go wrong to cause waste of resources and money.

Consequence reduction strategies primarily focus on identifying existing defects and stopping them from becoming failures. This strategy accepts risk along with the loss and waste from it. In contrast chance reduction strategies do not accept risk, waste or loss because they prevent the defects that cause failures from arising in the first place. Chance reduction proactively identifies risk and eliminates it.

Fortunately Ted, we can do something about it. There are two choices – get very good at fixing failures fast, or, don’t have failures in the first place - ZERO DEFECTS is the way to go.

**Risk ($/yr) =**

**Chance (/yr) x Consequence ($)**
The Risks You Live With and Those You Prevent Show Your Risk Boundary

If each failure costs your business $7,000 – $15,000 for every $1,000 of repair cost … what risk is the business willing to carry?

How often will a failure event be accepted?

• What failures don’t you bother repairing, but immediately replace with new? (The risks of using rebuilt equipment are too much.)
• Which production equipment will you let fail? (The cost of failure is insignificant.)
• Which production equipment will you never allow to fail? (The cost of failure is too expensive.)
• When will you be willing to replace equipment that you will not allow fail? (How much remaining life are you willing to give up to reduce the risk of failure?)
• What size safety and environmental failures will you allow? (Their cost is insignificant.)

In the slide we have set a DAFT Costs limit of $10,000 per time period (usually a year). That means we will not accept any failures that cause us to spend more than $10,000 a year on that piece of equipment. To prevent spending more than that much money we must introduce risk prevention strategies to limit our risk to $10,000 per period. This approach forces us to look seriously at what is causing the risk and to develop solutions to limit and control it.

The ‘bent’ line at the top of the ‘Accept’ area is there because we have limited risk to $10,000 for the whole time period, regardless of what causes the failure and how expensive it ends up becoming. Since ‘Risk = Chance x Consequence’, it means that for the Consequence to stay at $10,000 we have to change the Chance of a failure event happening. An example is when the DAFT Cost is say $100,000 (i.e. anytime the repair cost is $10,000 – which is easy to spend these days) we must reduce the Chance of the event happening to 0.1 (i.e. 10%) of a $10,000 event happening. In that case ‘Risk = $100,000 x 0.1 = $10,000’ and we are still at our acceptance boundary.

You can also look at the risk boundary in another way. A more complete version of the risk equation is:

‘Risk = Consequence x No of Opportunities x Chance an Opportunity becomes a Failure Event’

With risk in this form you can see that to keep to $10,000 a year total, you cannot have a $100,000 failure more than once in every 10 years (Risk = $100,000 x 1 x 0.1 = $10,000).
Set an Acceptable Equipment Failure Domain & Manage Your Business Risk to It

The failure domain is set by the cost of a failure event and the frequency you will accept it. If you set a $10,000 per year limit as your risk boundary, then that value can be reached in many ways. The risk equation now becomes Risk $/yr = $10,000/yr = Consequence from Failure x Opportunities for Failure x Chance of Failure. You now have three variables in play with limitless combinations that satisfy the equation.

In the slide the shaded volume is if the consequence is set at $10,000 and the opportunities and chance vary. The red dotted line is if all three variables change. It tells us that we will accept a $1M event if it only has a 10 percent chance of happening once in ten years. That is still equivalent to $10,000 per year.

The crazy thing would be to live with the risk if a single $1M event if it will bankrupt the business. Though the mathematics says $10,000/yr is equal to 10% of $1M spent equally over ten years, the fact is that though$10,000/yr is manageable to a business, a $1M event would destroy it.

In reality your tolerance for a $1M failure event is NEVER if such an event will ruin you. We cannot make our risk choices by mathematics alone; we must make them on what you can afford to lose!
Example of Using a Risk Boundary

Putting your risk boundary onto a risk matrix turns a difficult concept like risk, which involves ever-changing chance and consequences, into a simple visual representation of the current risk situation from a failure scenario in a company.

In this slide the conveyor return roller failed long ago and now the conveyor belt running over it is wearing away the tube wall at the right hand side of the roller. Once that happens the edge of the hole that appears in the tube becomes a knife edge. The knife edge is always in contact with the moving belt. Once the knife edge appears it creates an opportunity for the belt to be ripped its full length. As the hole gets bigger in the tube it grows both circumferentially and toward the centre of the roller. The opportunity to catch the underside of the belt with the knife edge and rip it full length continually rises. A ripped belt would lose the company $200,000 DAFT Cost.

But much worse than a ripped belt is the possibility for the knife edge to become a peeler and scrape the rubber belt into a large volume of rubber shavings. The thin rubber shavings are taken by the moving belt to the conveyor drive where they build-up around the motor. As the motor gets hotter and hotter from lack of ventilation the rubber shavings catch fire and the entire conveyor system and its drive is completely burnt. To replace the damage of a conveyor system fire would be $2,000,000 DAFT Cost.

The consequence and chance of each scenario is easily plotted on the risk matrix. From doing regular maintenance for $1,000 per year, to the $12,000 cost to replace a failed roller, to the $200,000 loss of a ripped belt and finally the $2,000,000 rebuild of a burnt system the risk situation is clear to see on the matrix. It is now up to Production and Maintenance to decide how to handle the risk.
Risk – Reduce Chance or Reduce Consequence?

The Figure lists some of the current methods available to address risk. The various methods are classified by the Author into chance reduction and consequence reduction strategies. This slide categorises many of the maintenance and reliability strategies now available into either Chance Reduction Strategies or Consequence Reduction Strategies. Maintenance Planning and Scheduling is a proactive chance reduction strategy because it aims to control maintenance work so that it reduces the possibility of defects and errors being introduced by the maintainers into the plant and equipment.

Several observations are possible when viewing the two risk management philosophies. Consequence reduction strategies expect failure to happen and then they manage it so least time, money and effort is lost. The consequence reduction strategies tolerate failure and loss as normal. They accept that it is only a matter of time before problems severely affect the operation. They come into play late in the life cycle when few risk reduction options are left.

In comparison, the chance reduction strategies focus on identification of problems and making business system changes to prevent or remove the opportunity for failure. The chance reduction strategies view failure as avoidable and preventable. These methodologies rely heavily on improving business processes rather than improving failure detection methods. They expend time, money and effort early in the life cycle to identify and stop problems so the chance of failure is minimised.

Both risk reduction philosophies are necessary for optimal protection. But a business with chance reduction focus will proactively prevent defects, unlike one with consequence reduction focus that will remove defects. Those organisations that primarily apply chance reduction strategies truly have set-up their business to ensure decreasing numbers of failures, and as a consequence they get high equipment reliability, and reap all the wonderful business performance it brings.
Joe, we’ve gone over the hour.

Right, see you tomorrow. … Between now and then think about: Where does the production time go each day?

Yea, … sure ….

Humm … what’s that got to do with maintenance?

Joe sets Ted a second trick question.

Come in Ted.

So then … Where does the production time go each day?

What about meal times? What about during change-overs? What about an equipment breakdown? What if we make rejects? What if the plant runs at half speed?

If we lose too much time we will need to buy extra equipment to make the product that should have been made during the time we lost. We end-up building a second factory to make what should have been made in one factory.

They meet the next day …

Hi Joe.

Production make product each day.

Oh, … I see, … those are times of lost production.

Joe is right. There are only so many hours in a day. If they are not used productively to make quality product then the opportunity is lost, and what could have been done in that time will
never be made. Any operating time not spent making quality product at full capacity is forever lost. Future time is now needed to make product that should have already been made. That lost time can grow to become a big waste that saps the efforts and energy of a business’ people. And because not enough product is being made the business’ managers ‘think’ they need to buy more plant and equipment to increase capacity; capacity they already had but was lost to wasted time.

Discovering the Hidden Factory

If you want to know how big your ‘hidden factory’ is, you only need to record all the times and the reasons that production is stopped, when rejects are made, and when production is below 100% capacity. When you fix all the causes that produce the losses you will very likely have a second factory for free.

Plant capacity can be increased by putting the ‘hidden factory’ to work.
How Maintenance Planning & Scheduling Help to Reduce Unit Cost of Production

The ‘Hidden Factory’

Maintenance and Production unearth the ‘hidden factory’ when they work correctly, accurately, safely, right first time.

The ‘hidden factory’ is all the production capacity lost due to the unnecessary waste of operating time and production rate. It can total to more than half of the plant and equipment capacity in those organisations that are not aware of their time and production wastes. To find the size of the ‘hidden factory’ it is necessary to measure actual performance against the maximum rated potential of the operation. The difference between the two—maximum possible and actual achievement—is the size of your ‘hidden factory’.
Most Business make their Machines Break

This is a statistically stable process of breakdown creation – this business makes breakdowns as one of its ‘products’.  

It is a surprise to learn that most businesses destroy their own machines. The slide shows the history of equipment breakdowns in a plastic pipe manufacturing business. Once you create the timeline of weekly number of breakdowns, or the weekly hours spent on breakdowns (as in the plot shown) you can see how stable the process of breakdown generation is in a business.

Notice that every week there were breakdowns. Some weeks were a complete disaster, and some were not so bad – only a few lost. If the graph is representative of normal operation, the time series can be taken as a sample of their typical business performance.

The results have been put into a control chart and limits placed at 3 sigma distances (The least number of breakdowns can only be zero, so the lower limit is 0). The average breakdown hours per week are 31 hours. Assuming a normal distribution, the standard deviation is 19 hours. The Upper Control Limit, at three standard deviations, is 93 hours. The Lower Control Limit is zero.

The fact that all results are within the 3 sigma process limits tells us that this process is stable. Since all data points are within the statistical boundaries, the analysis indicates that the breakdowns are common to the business processes and not caused by outside influences. This company will always have an average number of 31 hours lost weekly to breakdowns. This company makes

Business process performance is mostly in our control. We improve our processes by choosing the policies and practices that reduce the chance of bad outcomes and events happening, and that increase the chance of good events and outcomes occurring. Often business process variability fits a normal distribution curve, like in the Figure\textsuperscript{3}. When things are uncontrolled, the process produces a range of outputs that could be anywhere along the curve.

\textsuperscript{3} Many real-world process outputs are normally distributed, but distributions can also be skewed or multi-peaked.
breakdowns as one of its products!

Analysing if Your Business has a Stable Process of Causing Breakdowns

This slide shows the raw breakdown data from the plastic pipe manufacturer over the weeks of the investigation. It’s easy to put the weekly results into a spreadsheet and plot the graphs. The distribution of hours in the bottom bar chart shows a two-peak plot. The weeks in which there were many hours lost are not the same situations as the ‘normal’ weeks of hours lost on breakdowns. When investigated the large hours were due to severe breakdowns that sucked many people into their repair. Normally the breakdowns are small and easy to fix because the people in the operation have become experts at fire-fighting.

In the three weeks following the period represented in the Figure the weekly breakdown hours were respectively 25, 8 and 25 hours. This business has built breakdowns into the way it operates because the process of breakdown manufacture is part of the way the company works. The only way to stop breakdowns in future is to change to processes that prevent breakdowns.

The way to tackle variability is to put a limit on the acceptable range of variation and then build, or change, business processes to ensure only those outcomes can occur. Set a minimum specification of performance for a process producing wide variation then introduce the precision control requirements of an Accuracy Controlled Enterprise. Only those outcomes that meet or better the ‘good’ standard are acceptable. All the rest are defects and rejects to be analyzed, their causes understood and then removed forevermore.
What Operation Risks do You Live With?

Current application of CBM is typically on critical machines ... what of the rest?

- CBM = Condition Based Maintenance
- PdM = Predictive Maintenance

Machines by size

300KW: 10%
50-300KW: 25%
0-50KW: 65%

Percent of Maintenance Budget

Stethoscope    Laser Thermometer    Touch Thermometer    Vibration Pen    Operator & Checklist

First use low-tech options to monitor ... then hi-tech to investigate problems.

The trap many operations fall into is to focus much condition monitoring effort on the critical plant and discount the importance of monitoring the remaining equipment. In reality the key equipment is naturally high in priority and people are well aware of the consequences of failure. This focus tends to help keep reliability and availability high by applying condition monitoring to detect impending failures. As a result it is possible that the rest of the plant will end up suffering more downtime from lack of attention.

The company represented in the slide spent most of its maintenance moneys on breakdowns of low priority equipment. They looked after the high criticality plant and medium criticality plant well, but could not justify the expense of condition monitoring low criticality equipment. In such situations it becomes necessary to find methods to also condition monitor all the ‘less important’ items of plant and equipment so that the breakdowns, which cost far more than planned work, do not arise.

One method is to use the human senses of operators and maintainers and supplement them with simple monitoring tools to conduct regular inspections of all your equipments’ condition. When they detect a problem a thorough examination can be done with more expensive technology if it is warranted. In this way the regular observations you will reduce the number of breakdowns and save maintenance expenditure since fewer failures will occur.

Risk is virtually impossible to reckon exactly because it is probabilistic – a situation might happen, or it might not. Risk is a power law (that means its effects can vary to extremes unpredictably) and the same level of risk can be arrived at in an infinite number of ways. People will model and quantify risk to give it a firm value, but the results are notoriously misleading because real situations are unlikely to behave in the way they are imagined, unless they follow a well rehearsed script. The mathematics for gauging risk is straightforward and can be calculated in a spreadsheet, or rated with the help of a risk matrix. Identifying the inherent risk profile present is the first step in matching mitigation strategies to the risk.
Condition Monitoring the Japanese Way

The Japanese use their plant operator’s five physical senses along with modern non-destructive testing methods and technology to condition monitor their equipment. They maximise the use of non-intrusive maintenance.

The table shows the types of technology based condition monitoring used, where they were used and what they were used to detect. The focus was on detecting abnormalities before failure occurred. This was the theme the Japanese constantly enforced – the prevention of failure! They did not want unexpected stoppages. They were focused on detecting variation from normal and removing it so that they could maximise equipment performance and production results.

Interestingly, process pumps were not vibration-monitored. The Japanese engineers were asked why no vibration analysis was done on the pumps. They said that precision alignment was done using the twin reverse dial indicator method and as long as the alignment was to specification and tolerance they did not see any advantage in also vibration monitoring the pumps as they would be running as perfectly as was possible.

When a precision alignment was done and the operators performed their sensory checks and inspections there was confidence in being able to detect equipment problems before failure. Vibration analysis was used only on critical equipment and on expensive equipment. All other operational monitoring was by the operators.

The Japanese make great use of their operators in doing their plant’s maintenance. The operators do as much minor maintenance as possible and they use their five senses to condition monitor their plant. Technological tools are also used for condition monitor, but the operator is seen as the ‘front line’ of defence against failure.

Many visual inspections of wearing parts are done to establish the working life of an item. The working life is then known and the PM-10 plan is updated to include change-out before the item life is up.
Risk that is of low consequence, but happens often, is just as costly as those that happen occasionally but are expensive when they do. Neither situation is acceptable and they must be removed if you want to minimise disruptions to production.
This Figure shows a log-log graph of risk. When plotted on log-log axes risk forms straight lines on the plot. That a power law is a straight line on a log-log plot means that randomness exists in the behaviour of the influencing factors. A lot of human activities plot straight on log-log plots. Superimposed in the plot is a risk matrix that uses colour to indicate the severity of risk depending on the cost of the problem and the number of times it happens. This is how risk matrices are developed. Notice how the ‘red’ cell is at the top, right of the matrix.
What Extreme Risk Really Means

The slide shows a typical risk matrix used in industry. Notice how the high risk portion, which was a small part in the log-log plot, has become a large part of the lower risk matrix. This is the effect of converting risk, which is power law, back into a linear scale. We must be very careful when using the standard risk matrix that we do not make everything into a high risk just because it occupies a large part of the matrix. We must realise that it is unrealistic that all risky situations have a high risk. In reality high risk is the exception, rather than the rule.

Professor James Reason developed the ‘Swiss cheese’ model of risk.

- Each threat or escalation barrier can be represented as a piece of Swiss cheese
- The holes represent weaknesses in the processes that form part of the barrier. The weakness can relate to the design of the process or its implementation.
- If the holes in the threat barriers line up this forms the chain of events that lead from a hazard to an event.
- If the holes in the escalation barriers line up this forms the chain of events that leads from an event into a consequence.

This explains why often bad things happen but they do not automatically end in catastrophe. It takes a number of things to go wrong at the same time (i.e. the holes in the Swiss cheese line-up) before a disaster happens. But when it does, then the consequences can be life-ending.

The matrix also asks another question of us: is it better to spend a lot of money to fix one large risk, or to spend the same money and fix many small risks? If many small risks can be removed, the result will be fewer annoying little problems to overload us and take our attention away from controlling the large risks. With the small risks gone we can better manage the remaining large risks. In addition, with many small risks gone the probability (chance) of a small problem contributing to a larger problem also falls And that means you have even fewer large problems.
Joe asks Ted to think about the role of Maintenance.

Good day Ted.

Fine thanks. Did you get a chance to think about the question I left you with - What is Maintenance here to do?

So you like getting those 2am and 3am morning call-outs to fix the breakdowns? You like being an ‘overtime hero’?

The role of Maintenance is to reduce risk, and stop those ‘Swiss cheese’ holes lining up! What you get for the effort is the plant running well, making quality product at full capacity, problem-free. (And you can sleep-in at nights.)

How goes it Joe?

Yes. From what I can see, we are here to keep the place running.

No, I hate those. But what else can we do about them?

They meet again …

What Joe is saying is that Maintenance needs to manage the causes of failure so that the chance of a failure happening is very small. Especially the serious failures that disrupt production. The holes in the ‘Swiss cheese’ slices must either be closed-up, or stopped from lining-up.
Maintenance has the role of reducing risk by stopping what causes the problems that lead to failure.

The Risk Management Process

Risk $/yr = \text{Consequence }$ x \text{No of Opportunities /yr x Chance of Failure}

This is an extract from Australian Standard 4360, which is a copy of the equivalent ISO standard used internationally. The diagram shows the logical process to follow in identifying, measuring and managing risk. The methodology is well founded and tested, and if applied delivers control of risk in a situation.

The guide to the standard is very comprehensive in explaining the risk management process and has worked examples of how to apply the various steps.

The important point is that all situations contain risk, but no one knows which situation will go beyond normal levels of risk to become a major incident. This means that every situation must be treated as being possible to progress to disaster. The only protection is to implement a standard method of suitable risk control and ensure it is religiously followed. This includes conducting regular tests that the risk mitigation measures do work and are being followed by all parties.

Maintenance is a risk management strategy. When used as a chance reduction tool, maintenance is an investment spent proactively to prevent failure. As a result it delivers low-cost operation because few things go wrong. When maintenance is used as a consequence management tool it is applied after failure, and so it is wrongly seen as an expense to be minimised. Maintenance used to prevent failures is cheap; when used to repair failures it is expensive.
The Application of Risk Based Principles to Maintenance

Risk management methodology is an ideal fit to the maintenance function. It requires maintenance to apply sound risk identification and risk control principles to plant and equipment. By following a standard procedure to clarify the risk, like using international risk management guidelines, the appropriate strategies and practices can be identified and implemented.
Maximising Life Cycle Profits and Minimising Operating and Maintenance Costs

Equipment Life Cycle (say 20 years)

~ 10% of Life Cycle (~ 2 years) ~ 85% of Life Cycle (~ 17 years) ~ 5%

Idea Creation
Feasibility Design
Preliminary Design
Approval
Detail Design
Procurement
Construction
Commissioning
Operation
Decommissioning
Disposal

Time

DOCTOR uses risk analysis at the design stage to identify operating failure costs so they can be minimised.

Purchase Phase
Design Phase
Construction Phase

Future DAFT Costs

$ The Project Phase is the time to control the future costs of the operation.

All we can do during the operating phase is run and care for the equipment as it was designed to be. If the design requires expensive parts, and/or lots of downtime for maintenance and repairs, then the design is the problem, not the maintenance.

It is important to realise that operating costs can only be changed and removed during the design and project phase of the life-cycle. Once plant and equipment is in place, all its associated requirements must be met. Those necessary costs cannot be lowered without increasing the risk of failure by reducing the items reliability, with subsequent poor effects on production output.

The Maintenance Planner can do nothing to change what happened during the project phase, it is all history by the time they go to work in the business. But they can change the project decisions to be made in future if they capture good, sound records of the performance and costs of the production equipment used in their operation. With believable evidence of equipment performance provided by the Maintenance Planner, future project designers will make better decisions in designing and selecting future operating plant.
Maintenance Planning is a risk management strategy that comes from the wide range of Operating and Maintenance strategies available to organizations. The Diagram shows a means of selecting appropriate project, maintenance and operating strategies matched to the size of risk carried by a business—it is called DOCTOR (Design and Operations Costs Totally Optimised Risk). The methodology optimises operating profit. It uses the more than 60 DAFT Costs that could happen from a failure, to determine the true cost of business risk and then matches life cycle operating and project risk control practices to the risk a company is willing to carry.

The DOCTOR rates operating risk while projects are still on the drawing board. If during operation a failure causes severe business consequences they are investigated and removed. Alternately they are modified to reduce the likelihood of their occurrence and limit their consequences. Pricing is done with DAFT Costing and the life cycle is modelled with Net Present Value (NPV) methods by the project group. Assuming a failure and building a DAFT Cost model identifies those designs and component selections with high failure costs. Investigating the cost of an ‘imagined’ equipment failure lets the project designer see if their decisions will destroy the business, or will make it profitable. The design and equipment selection is then revised to deliver lower operating risk. By modelling the operating and maintenance consequences of capital equipment selection while still on the drawing board, the equipment design, operating and maintenance strategies that produce the most life cycle profit can be identified.

Applying the DOCTOR allows recognition of the operating cost impact of project choices and the risk they cause to the Return On Investment from the project. The costs used in the analysis are the costs expected by the organisation that will use the equipment. Basing capital expenditure justification on actual operating practices and costs makes the project estimate of operating and maintenance costs realistic. By encouraging the project group to apply real costs of operation during the capital design and equipment selection, the consequent effect of their use on operating profitability can be optimised. Using DAFT Costing in design decisions simulates
the operational financial consequences to good accuracy and the design can be ‘tuned’ to get best life cycle operating results.

## Equipment Criticality

**Equipment Criticality =**

**Operating Risk =**

**Failure Frequency (/yr) x DAFT Cost Consequence ($)**

*Equipment Criticality is a business risk rating indicator.*

---

Equipment Criticality indicates risk to the business. It highlights how bad a situation can become if it is allowed to occur. The true financial impact on a business of a bad risk is only fully appreciated when the Defect and Failure True Costs (DAFT Costs) are completely known. Remember, if there is no failure there is no costs. Hence, there is good justification to spend money on preventing failure, because, if the failure is not stopped, it eventually will almost certainly occur, and then vast DAFT Costs will be spent.

The concept of Equipment Criticality is used to determine the importance of plant and equipment to the success of an operation. It provides a way to prioritize equipment so that efforts are directed towards the plant and equipment that delivers the most important outcomes for the business. Typically the Equipment Criticality is arrived at by Operations and Maintenance personnel sitting down and working thorough every item of equipment and applying the risk matrix to determine the risk to the enterprise should the equipment fail. The risk rating becomes the ‘Equipment Criticality’.

A more rigorous method, and one based on financial justification, is to use the ‘Optimised Operating Profit Method’. By applying DAFT Costs when calculating the risk from equipment failure to the enterprise, it permits each item of plant to be graded in order of true financial impact on the operation should it fail. The ‘Equipment Criticality’ then reflects the financial risk grading.
Equipment Criticality Matches Operational Priority to Business Risk

It is important that every item of plant and equipment be categorised, including every sub-system in each equipment assembly. We need to know how critical is the smallest item so we understand what is important to continued operation.

There have been many situations where smaller items of equipment, such as an oil circulating pump or a process sensor, were not identified for criticality and were not maintained. Eventually they failed and the operation was brought down for days while parts were rushed to do a repair. Be sure that you know how important every item of equipment is to your business.
Identify Your Equipment Risks and Priority Equipment

This table is the basic approach. There is full mathematical modelling, but this basic method is fine to start with. The layout is universal. You calibrate the consequences’ description to what you are willing to accept, and the costs to what you are willing to pay.

When the risk management process is applied a risk rating scale is developed to assess the size of a risk. Such a scale can be used to measure the impact on a business of an equipment failure. The greater the impact from failure and downtime the more that must be done to prevent it or reduce its consequence.
Develop an Equipment Criticality Matrix

<table>
<thead>
<tr>
<th>Item</th>
<th>Sub-About</th>
<th>Failure Modes</th>
<th>Likely Causes</th>
<th>DAFT Cost Rating</th>
<th>Likelihood</th>
<th>Criticality by Risk Matrix</th>
<th>Required Operating Practice</th>
<th>Required Maintenance</th>
<th>Criticality Overall Expenditure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td></td>
<td>1. Dirty Fuel</td>
<td>2. Blockage injectors</td>
<td>150,000</td>
<td>50</td>
<td>1</td>
<td>1 in 10,000hr</td>
<td>3 = 1 = M</td>
<td>1. Cut fuel to carry emergency stock</td>
</tr>
<tr>
<td>Fuel system</td>
<td></td>
<td>1. Contents</td>
<td>2. Water in</td>
<td>1. Damaged</td>
<td>2. Water pump</td>
<td>40,000</td>
<td>15</td>
<td>1 in 10,000hr</td>
<td>3 = 4 = H</td>
</tr>
<tr>
<td>Oil system</td>
<td></td>
<td>1. Snapped</td>
<td>2. Over</td>
<td>1. Snapped</td>
<td>2. Over</td>
<td>250,000</td>
<td>14</td>
<td>1 in 10,000hr</td>
<td>4 = 2 = H</td>
</tr>
<tr>
<td>Gear and pumps</td>
<td></td>
<td>1. Jammed</td>
<td>2. Over</td>
<td>1. Jammed</td>
<td>2. Over</td>
<td>150,000</td>
<td>100</td>
<td>TOTAL RISK = 7</td>
<td>6 = 6 = 6</td>
</tr>
<tr>
<td>Engine block</td>
<td></td>
<td>1. Over</td>
<td>2. Over</td>
<td>1. Over</td>
<td>2. Over</td>
<td>25,000</td>
<td>15</td>
<td>1 in 10,000hr</td>
<td>3 = 3 = M</td>
</tr>
<tr>
<td>Cooling system</td>
<td></td>
<td>1. Over</td>
<td>2. Over</td>
<td>1. Over</td>
<td>2. Over</td>
<td>20,000</td>
<td>15</td>
<td>1 in 10,000hr</td>
<td>3 = 3 = M</td>
</tr>
<tr>
<td>Ignition system</td>
<td></td>
<td>1. Over</td>
<td>2. Over</td>
<td>1. Over</td>
<td>2. Over</td>
<td>25,000</td>
<td>15</td>
<td>1 in 10,000hr</td>
<td>3 = 3 = M</td>
</tr>
<tr>
<td>Generators</td>
<td></td>
<td>1. Over</td>
<td>2. Over</td>
<td>1. Over</td>
<td>2. Over</td>
<td>150,000</td>
<td>100</td>
<td>TOTAL RISK = 7</td>
<td>6 = 6 = 6</td>
</tr>
<tr>
<td>Input shaft</td>
<td></td>
<td>1. Over</td>
<td>2. Over</td>
<td>1. Over</td>
<td>2. Over</td>
<td>20,000</td>
<td>15</td>
<td>1 in 10,000hr</td>
<td>3 = 3 = M</td>
</tr>
<tr>
<td>Internal gears</td>
<td></td>
<td>1. Over</td>
<td>2. Over</td>
<td>1. Over</td>
<td>2. Over</td>
<td>15,000</td>
<td>15</td>
<td>1 in 10,000hr</td>
<td>3 = 3 = M</td>
</tr>
<tr>
<td>Output shaft</td>
<td></td>
<td>1. Over</td>
<td>2. Over</td>
<td>1. Over</td>
<td>2. Over</td>
<td>15,000</td>
<td>15</td>
<td>1 in 10,000hr</td>
<td>3 = 3 = M</td>
</tr>
</tbody>
</table>

This is the approach used to identify equipment criticality. The criticality justifies adoption of suitable failure prevention practices and necessary maintenance strategies. It produces a priority scale to care for equipment, with equipment of the highest importance getting highest protection and response. By applying an equipment criticality rating to plant and equipment it provides guidance on the importance of installing protective measures and making available emergency recovery strategies after a failure.

The end result of the equipment criticality process is a table showing the Criticality Rating and impacts on the business of failure, the actions necessary to control the risks, along with who is responsible for them to be done.

The method makes it clear to management how the organisation suffers from failure and initiates the introduction of suitable practices to control the risk.

The criticality rating process is applied to plant and equipment in order to determine operating risk and address it with appropriate operating and maintenance strategies. It does not consider how the risks can be prevented in the first place, so that no risk is present to have to control. Such an approach requires a proactive method like the DOCTOR. I encourage organisations to do it. It is one of the most important steps to take on the journey to operating excellence.
Activity 1 – Equipment Criticality

Complete the example and identify the equipment criticality for the items of a mining truck.
### Activity 1 – Equipment Criticality and Risk Management Strategy Table

Using the risk matrix over the page, complete the criticality rate columns (E, H, M, L) for the mining truck and select the maintenance to apply and the operating practices to use to reduce risk.

<table>
<thead>
<tr>
<th>Item</th>
<th>Sub-Assy</th>
<th>Failure Modes</th>
<th>Likely Causes</th>
<th>DAFT Cost Rating</th>
<th>Likelihood</th>
<th>Criticality by Risk Matrix</th>
<th>Required Operating Practice</th>
<th>Required Maintenance</th>
<th>Criticality after Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td></td>
<td>1. Dirty Fuel</td>
<td>2. Blocked injectors</td>
<td>500,000</td>
<td>100</td>
<td>TOTAL RISK</td>
<td>1. Too expensive to carry emergency spare</td>
<td></td>
<td>? + ? = ?</td>
</tr>
<tr>
<td></td>
<td>Fuel system</td>
<td>1. Contaminated Oil system</td>
<td>2. Water in oil</td>
<td>25,000</td>
<td>23</td>
<td>1 in 30,000hr</td>
<td>2 + 3 = M</td>
<td></td>
<td>1. Use best practice oil store management methods</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40,000</td>
<td>15</td>
<td>1 in 20,000hr</td>
<td>2 + 4 = H</td>
<td></td>
<td>2 + 2 = M</td>
</tr>
<tr>
<td></td>
<td>Crank and pistons</td>
<td>1. Snapped con rod Oil system</td>
<td>1. Dust in oil</td>
<td>250,000</td>
<td>14</td>
<td>1 in 50,000hr</td>
<td>4 + 4 = H</td>
<td></td>
<td>1. Operator trained to not overload truck and over-rev motor</td>
</tr>
<tr>
<td></td>
<td>Engine block</td>
<td></td>
<td></td>
<td>150,000</td>
<td>28</td>
<td>1 in 80,000hr</td>
<td></td>
<td></td>
<td>2. Install wireless engine monitoring and reporting</td>
</tr>
<tr>
<td></td>
<td>Cooling system</td>
<td></td>
<td></td>
<td>20,000</td>
<td>15</td>
<td>1 in 10,000hr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ignition system</td>
<td></td>
<td></td>
<td>25,000</td>
<td>15</td>
<td>1 in 30,000hr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gearbox</td>
<td></td>
<td>150,000</td>
<td></td>
<td></td>
<td>100</td>
<td>TOTAL RISK</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input shaft</td>
<td></td>
<td>20,000</td>
<td></td>
<td></td>
<td>15</td>
<td>1 in 60,000hr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal gears</td>
<td></td>
<td>55,000</td>
<td></td>
<td></td>
<td>38</td>
<td>1 in 10,000hr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output shaft</td>
<td></td>
<td>15,000</td>
<td></td>
<td></td>
<td>15</td>
<td>1 in 20,000hr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casing</td>
<td></td>
<td>50,000</td>
<td></td>
<td></td>
<td>60</td>
<td>1 in 30,000hr</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Adapted from AS 4360-2004 Risk Management

<table>
<thead>
<tr>
<th>Probability</th>
<th>Historical</th>
<th>Time Scale</th>
<th>Likelihood</th>
<th>Probability</th>
<th>Historical</th>
<th>Time Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;1 in 10</td>
<td>Is expected to occur in most circumstances</td>
<td>Once per year</td>
<td>5</td>
<td>Almost Certain</td>
<td>M</td>
<td>H</td>
</tr>
<tr>
<td>1 in 10 - 100</td>
<td>Will probably occur</td>
<td>Once every 3 years</td>
<td>4</td>
<td>Likely</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>1 in 100 – 1,000</td>
<td>Might occur at some time in the future</td>
<td>Once per 10 years</td>
<td>3</td>
<td>Possible</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>1 in 1,000 – 10,000</td>
<td>Could occur but doubtful</td>
<td>Once per 30 years</td>
<td>2</td>
<td>Unlikely</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>1 in 10,000 – 100,000</td>
<td>May occur but only in exceptional circumstances</td>
<td>Once per 100 years</td>
<td>1</td>
<td>Rare</td>
<td>L</td>
<td>L</td>
</tr>
</tbody>
</table>

### Consequence

- **People**: Injuries or ailments not requiring medical treatment. Minor injury or First Aid Treatment Case. Serious injury causing hospitalisation or multiple medical treatment cases. Life threatening injury or multiple serious injuries causing hospitalisation. Death or multiple life threatening injuries.
- **Reputation**: Internal Review Scrutiny required by internal committees or internal audit to prevent escalation. Scrutiny required by clients or third parties etc. Intense public, political and media scrutiny. E.g. front page headlines, TV, etc. Legal action or Commission of inquiry or adverse national media.
- **Business Process & Systems**: Minor errors in systems or processes requiring corrective action, or minor delay without impact on overall schedule. Policy procedural rule occasionally not met or services do not fully meet needs. One or more key accountability requirements not met. Inconvenient but not client welfare threatening. Strategies not consistent with business objectives. Trends show service is degraded. Critical system failure, bad policy advice or ongoing non-compliance. Business severely affected.
- **Financial**: $10K $30K $100K $300K $1,000K

### Risk Likelihood & Probability

- **Insignificant**: Risk must be reported to Senior Management and require detailed treatment plans to reduce the risk to Low or Medium.
- **Minor**: Needs senior management attention.
- **Moderate**: High risk – needs senior management attention.
- **Major**: Medium risk – specify management responsibility.
- **Catastrophic**: Low risk – manage by routine procedures.

<table>
<thead>
<tr>
<th>Probability</th>
<th>Historical</th>
<th>Time Scale</th>
<th>Likelihood</th>
<th>Probability</th>
<th>Historical</th>
<th>Time Scale</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Is expected to occur in most circumstances</td>
<td>Once per year</td>
<td>5</td>
<td>Almost Certain</td>
<td>M</td>
<td>H</td>
</tr>
<tr>
<td>1 in 10 - 100</td>
<td>Will probably occur</td>
<td>Once every 3 years</td>
<td>4</td>
<td>Likely</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>1 in 100 – 1,000</td>
<td>Might occur at some time in the future</td>
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<td>3</td>
<td>Possible</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>1 in 1,000 – 10,000</td>
<td>Could occur but doubtful</td>
<td>Once per 30 years</td>
<td>2</td>
<td>Unlikely</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>1 in 10,000 – 100,000</td>
<td>May occur but only in exceptional circumstances</td>
<td>Once per 100 years</td>
<td>1</td>
<td>Rare</td>
<td>L</td>
<td>L</td>
</tr>
</tbody>
</table>
## Risk Identification and Analysis – Template 1

<table>
<thead>
<tr>
<th>REVIEW DATE</th>
<th>BUSINESS UNIT NAME</th>
<th>COMPILED BY</th>
<th>FUNCTION ACTIVITY</th>
<th>REVIEWED BY</th>
</tr>
</thead>
</table>

### The Risk

**What can happen?**

**Source**

**How can this happen?**

### Impact

**Impact from event happening**

### Current Control Strategies

**Current risk level**

#### Likelihood

- (A) – Adequate
- (M) – Moderate
- (I) – Inadequate

#### Consequence

#### Current Risk Level

#### Acceptability (A/U)

---

- 58 -
## Risk Treatment Schedule and Action Plan – Template 2

<table>
<thead>
<tr>
<th>Risk Reference</th>
<th>Potential Treatment Options</th>
<th>Costs &amp; Benefits</th>
<th>Treatment to be Implemented (Y/N)</th>
<th>Risk Level After Implemented</th>
<th>Responsible Person</th>
<th>Timetable for implementation</th>
<th>Monitoring strategies to measure effectiveness of Risk Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**FINAL Cumulative Risk Level after Treatment**
Choosing of Maintenance Type

**Simplified RCM Method**

- **Consequence of failure acceptable?**
  - yes
  - no
  - **Hidden Failure**

- **Life reasonably predictable?**
  - yes
  - no
  - **Condition Monitoring practical?**
    - yes
    - no
    - **Condition Monitoring economic?**
      - yes
      - no

- **Plant Change**
  - yes
  - no
  - **Design out cause of failure practical?**
    - yes
    - no
    - **Designing out cause of failure economical?**
      - yes
      - no

- **Repair/Replace On-Condition maintenance**
  - yes
  - no

- **Repair/Replace on Time based maintenance**
  - yes
  - no

- **Run to Failure and Timely Repair/Replace**
  - yes
  - no

- **Failure Finding and Timely Repair/Replace**
  - yes
  - no

**Be wary choosing to do Breakdown Maintenance if you have not done a full DAFT cost. Breakdown Maintenance is 7 – 15 times repair cost. A $10,000 repair really costs a business between $70,000 to $150,000. You can buy a lot of maintenance for that!**

This chart is an alternate means to decide the maintenance strategy to use on equipment based on reliability centred maintenance principles.

**Match Maint Type to Equipment Criticality**

**Risk Based Method**

Once you decide the criticality, you match the type of maintenance to it by using this risk based chart, or the next one, which uses the inherent reliability of the item as the criteria.

- **Equipment**
  - Y
  - N

- **Hazardous, Safety, Environmental dangers from process**
  - Y
  - N

- **Breakdown, stops production, affects quality**
  - Y
  - N

- **Affects downstream plant**
  - Y
  - N

- **Can be fixed on-line**
  - Y
  - N

- **Time Based Maintenance**
  - S
  - A

- **Condition Based Maintenance**
  - B

- **Breakdown Based Maintenance**
  - C

**S = Security ; A,B,C = Maintenance Type**
This chart is used by Sumitomo Chemicals to determine what maintenance type to apply to their equipment.

**A Japanese way to decide equipment criticality.**

How do you decide what level and type of maintenance to use on an individual item of plant and its sub-assemblies? Not all equipment is equally important to your business. Some are critical to production and without them the process stops. Others are important and will eventually affect production if they cannot be returned to service in time. While other items of plant are not important at all and can fail and not affect production for a very long time.

As a maintainer you want to know which equipment in your plant falls into each of those categories so you can determine your response. Furthermore you want to know which sub-assemblies in each item of equipment are critical to the operation of the machine.

From this information you can decide which spares to hold on-site and which to leave as outside purchases. The equipment criticality also determines what level of preventative maintenance to use, what type and amount of condition monitoring to use and what type and amount of observation is required from the operators. You can also use it to justify on-line monitoring systems to protect against catastrophic failure.

The western approach to determine criticality is often to use either Reliability Centred Maintenance or Risk Based Maintenance to determine consequences of failure and then address the appropriate response to prevent the failure. The Japanese chemical manufacturing company I visited had a novel way of determining their equipment criticality. They based the equipment and component criticality on the knock-on effect of a failure and the severity of the consequences. It is the same intention as the previously mentioned methods but they arrive at the rating and the response to it in a unique, quick four-step process.

They used a simple flow chart that production and maintenance worked through together, equipment by equipment. Those failures that caused safety and environmental risks were not allowed to happen and either the parts were carried as spares and changed out before failure or the plant item was put on a condition monitoring program. Those failures that caused production loss or affected quality also were either not allowed to happen or put into a condition-monitoring program. And those failures that didn’t matter were treated as a breakdown.

The flow chart let one arrive at a rating and a corrective action for each piece of equipment and component fast. No need to spend hours and days looking at failure modes and deciding what to do about them. If an equipment or component loss produced dangerous situations, or if the failure stopped production or affected quality, it was either changed out before the end of its working life or it was put on a monitoring program.

The maintenance philosophy for every bit of plant could be arrived at in a four-step decision process. It was very easy to use and to decide what action to take.

The SABC is the criticality rating scale. On the chart you notice that equipment gets an ‘S’ rating when it is never permitted to fail because of serious danger to life and the environment from a failure. Under the ‘S’ rating parts are replaced before they reach the end of their working life. An ‘A’ rating also requires parts to be changed before the end of their working life but that is because of the production problems a failure would cause. A ‘B’ rating required condition monitoring. And a ‘C’ rating meant breakdown maintenance was acceptable. The SABC chart is both a criticality scale and a maintenance strategy decision tree.
The SABC criticality-rating chart was also used to determine the critical parts within the machine. The same decision logic was applied to the equipment’s components. From that review process the critical spares were determined and a decision made to either stock them or to monitor their condition and look for deterioration.

**Equipment Criticality for Subassemblies Too**

<table>
<thead>
<tr>
<th>RANK</th>
<th>MAINT TYPE</th>
<th>And in the same piece of equipment apply the same logic to the sub-assemblies.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.</td>
<td>TBM.</td>
<td>Bearing, Mech. Seal &gt; TBM</td>
</tr>
<tr>
<td>A.</td>
<td>TBM.</td>
<td>V-belt &gt; CBM</td>
</tr>
<tr>
<td>B.</td>
<td>CBM.</td>
<td>Oil gauge &gt; BM</td>
</tr>
<tr>
<td>C.</td>
<td>BM.</td>
<td></td>
</tr>
</tbody>
</table>

*Here’s a tip:* If the failure of a part will stop production, the DAFT Cost will be so huge that it must never happen. If the failure of a part does not stop production, then do breakdown maintenance, **UNLESS it is critical to safety, health or the environment.** If you come across parts in the plant that don’t need to be there, check with the designers and operators, and if they aren’t needed get rid of them and save the maintenance.

Parts that must never fail are changed out in a time-based cycle, parts that wear out unpredictable are monitored and parts that do not matter if they fail are brought when they break.
What Situations will Cause Parts to Fail?

A Bill of Material is a powerful document for deciding the maintenance to do on machine parts. You take one part number at a time and ask how many ways can it fail, or be failed. As you identify the causes of the failure you can make good maintenance strategy choices and identify what preventive and predictive actions to take.
Identify Equipment Assemblies and Parts at Risk of Failure

* Wear-out (age/usage related failure) > PM inspection
+ From Usage (contaminate with use) > PM renewal
• Induced Stress (random failure) > PdM condition
^ Installation Error (early life failure) > PrM/PrO precision
> ACE 3T procedures

Simply mark-up the Bill of Material with the failure types that can destroy a part, and as you collect and analyse the causes of failure it becomes clear how to protect the equipment and its parts with the right operating practices and maintenance strategies.

<table>
<thead>
<tr>
<th>Process Item Tag Maint</th>
<th>Type</th>
<th>&gt;Main Parts</th>
<th>Maint Type</th>
<th>Maint Freq</th>
<th>Spare Parts</th>
<th>Summary of Maintenance Trouble</th>
<th>Trouble</th>
<th>Maintenance / Check Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digester Pump BM</td>
<td>P-407A/B</td>
<td>TBM</td>
<td>Bearing</td>
<td>2T</td>
<td>Y</td>
<td>Based on TBM for bearing. Other parts arranged same time.</td>
<td>Bad actuation because of wearing of parts making contact with liquor</td>
<td>Control oil level and quantity of mechanical seal water</td>
</tr>
<tr>
<td>TBM</td>
<td>Mech seal</td>
<td>2T</td>
<td>Y</td>
<td>In case of occurred following trouble, deal with CBM each time.</td>
<td>Wearing of 2nd booster pump (P457B), installed vvvF</td>
<td>Check the delivery pressure/flow rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBM</td>
<td>V belt (2T)</td>
<td>Y</td>
<td>Becoming bad actuation because of wearing, leak of mechanical seal, damage of V belt</td>
<td>V belt becoming bad actuation because of wearing, leak of mechanical seal, damage of V belt</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBM</td>
<td>Impeller, casing</td>
<td>Y</td>
<td>Keep spare pump (A&amp;B is same specification)</td>
<td>Keep spare pump (A&amp;B is same specification)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spiral 6-402A</td>
<td>TBM</td>
<td>Body</td>
<td>1Y</td>
<td>Overhaul (legal check)</td>
<td>Scalloping on ball check caused by erosion/corrosion at around ball check</td>
<td>Check the entry point</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>Gasket</td>
<td></td>
<td></td>
<td></td>
<td>Thickness measurement (only outside casing)</td>
<td>Pressure test, visual check</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Scaling at high temperature side.</td>
<td>Visual check</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manual</td>
<td>Y type valve</td>
<td>BM</td>
<td>Body</td>
<td>Y</td>
<td>Seal with BM</td>
<td>Blocks of different valves (especially high temperature liquor)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Finally, you put it all together into a table, which reflects the decisions used to control risk. This table contains all the details, and drives all maintenance done on the plant and equipment.

Select timing of maintenance so a failure has the least chance of happening. This automatically minimises cost because there will be fewer failures to cause DAFT Costs.
These are what go into your standard maintenance and operating procedures and planned maintenance work orders. Once the criticality ratings are determined for each machine, and its components, a spreadsheet is developed listing the applicable maintenance strategy and the maintenance tasks to be used on the equipment. The complete maintenance philosophy, spare parts requirements, condition monitoring and preventative requirements, and the maintenance frequency for every item of plant are all there on one sheet for all to see. With this spreadsheet done first, it is an easy matter to transfer all of the required inspections and checks into a CMMS and generate preventative and corrective maintenance work orders to care for the equipment.

Hey Joe, that’s enough for today.

It has been a bit intensive, hasn’t it?… Here is today’s question for you to think about: *Why do parts fail?*

Okay, …See you later.

Finally, …a question I know something about?

Joe sets Ted another question.
Good morning Joe.
I thought of two reasons. One is because they wear out, the other is because they are overloaded.

Why is that important?

If we can extend the time between failures it’s where the big money is! Quality production, at full capacity, needs parts to perform at design service. As long as the parts meet all design conditions, they won’t fail. And if our parts don’t need maintenance because there is nothing wrong with them, then we get both lower cost and more production.

Hello Ted.
Did you work out why do parts fail?

Very good Ted. I can only add one more important factor. And that is time – when will they fail? – when will the parts finally come to the end of their usable lives?

Understand How Machines are Designed

TIP: THE SECRET TO GREAT EQUIPMENT LIFE IS TO ...
KEEP PARTS WITHIN THEIR DESIGN STRESS ENVELOPE!

Ted, when they design machines, like this shaft rotating in two bearings, they keep the parts in place by making the gaps between them very small. The hair on your head is about 0.1 mm (0.004") thick. On this 25 mm (1") shaft, the gap between the metal surfaces can be as small as 0.01 mm (less then 0.0005"). That is 10 times thinner than the thickness of your hair. That is very little space for things to move in. If the parts get twisted and distorted then that clearance disappears and you have parts hitting each other. Any machine in that situation will quickly fail.

In the sketch the bearing diameter ranges 25.01 to 25.025 mm. Shaft diameter ranges 24.975 to 24.99 mm. Bearing to Shaft diametric clearance ranges from a possible low of 0.02 mm (0.0008") to a maximum of 0.05 mm (0.002") So a radial movement of 0.01 (0.0004") to 0.025
mm (0.001”) will cause a clash of shaft and bearing. There is no forgiveness in machines when they are pushed and distorted beyond their design capability. Understand that machines need to be cared for in service by using them as the designer intended and by keeping them within the limits the designer expected.

The Unforgiving Nature of Machine Design

How far off-center did the designer allow the shaft to move? How much movement/angle did the bearing designer allow? How much distortion before the parts overload and fail?

Ted, those tight clearances mean that everything has to be exactly as the designer planned it to be. The whole machine needs to be running precisely as it should be. If the parts are deformed outside of their tolerance, like in this sketch, then the bearings will fail in a matter of hours, and not the years that they should last in a machine that was working as it was designed to be.

Remember: The Limit of Machine Distortion is set by Design Tolerances – don’t let a machine or its parts get twisted out of shape!

As soon as machine parts deform outside of tolerance limits they’re on the way to early failure.
Stress from Distortion

Far too common examples of soft-foot problems!

Here are common situations where soft-foot occurs. If the items are bolted down without fixing their soft-foot problem, the equipment is distorted out-of-shape, or the mounting feet do not fully contact the base and properly support the forces created when the equipment is used.

Another common problem is shaft misalignment that distorts and bends shafts, which in turn combines with running loads and can overload the shaft bearings when the machine is operating with normal duty loads.
Physics of Failure

The load on a part causes stress in the part. This load comes from the environment in which the part lives. This environment can have a range of possible load conditions. We show the pattern of varying loads that a part can experience as a curve from least load to most load.

Why do parts fail? Because they can no longer handle the stress they suffer. When the load is too great the part fails from 'overload', when the material weakens and degrades it fails from 'fatigue'.

Plant, machinery and equipment can only be expected to be reliable if kept within the design stresses and the internal and external environmental conditions it is designed to handle. Once the stresses or environment conditions are beyond its capability, it is on the way to an unwanted breakdown at sometime in future.

Theoretically, if the strength of materials is well above the loads they carry, they should last indefinitely. In reality, the load-bearing capacity of a material is probabilistic, meaning there will be a range of stress-carrying capabilities. The distributions of material strength in the Figure show the probabilistic nature of parts failure as a curve of the stress levels at which they fail. The range of material strength forms a curve from least strong to most strong. Note that the y-axis represents the chance that a failure event could happen and that is why the curves are known as probability density functions of ‘probability vs. stress/strength’. They represent the natural spread and variation in material properties.

The loads on a part cause stresses in the part. When the stress exceeds a part’s stress carrying capacity the part fails. The stress comes from the use and operation of the part under varying load conditions. Use a part with a low stress capability where the probability of experiencing high loads is great, and there is a good chance that a load will arise that is above the capacity of the part. The weakest parts fail early; the strongest take more stress before they too fail.

The equipment designer’s role is to select material for a part with adequate strength for the expected stresses. The top curves of the Figure show a distribution of the strength-of-material used in a part, alongside the distribution of expected operational stresses the item is exposed to. If the equipment is operated and maintained as the designer forecasts there is little likelihood that the part will fail and it can expect a long working life, because the highest operating stress is well below the lowest-strength part’s capacity to handle the stress. The gap between the two extremes of the distributions is a factor of safety the designer gives us to accommodate the unknown and unknowable.
However parts do fail and the equipment they belong to then stops working. Certain causes of equipment failure are due to aging of parts, where time and/or accumulated use weakens or removes the materials of construction. This is shown in the bottom curve, where the part’s material properties are degraded by the accumulated fatigue of use and age until a proportion of the parts are too weak for the loads and they fail.

The top curves represent the situation where operating stresses rise and overloads are imposed on small areas of parts. The operating stresses grow huge, and in some situations they are so large that they exceed the remaining material strength and the part fails.

The operating lives of roller bearings is an example where the effects of high local stresses cause equipment parts failure. Depending on the lubricant regime (hydrodynamic, elastohydrodynamic), viscosity, shaft speed and contact pressures, roller bearing elements are separated from their raceways in the load zone by lubricant thickness of 0.025 to 5 micron. Eighty percent of lubricant contamination is of particles less than 5 micron size. This means that in the location of highest stress, the load zone, tiny solid particles can be jammed against the load surfaces of the roller and the race. A solid particle carried in the lubricant film is squashed between the outer raceway and a rolling element. Like a punch forcing a hole through sheet steel, the contaminant particle causes a high load concentration in the small contact areas on the race and roller. An exceptionally high stress punches into the atomic structure, generating surface and subsurface sub-microscopic cracks. Once a crack is generated it becomes a stress raiser and grows under much lower stress levels than those needed to initiate it.

Exceptionally high stresses can also result from cumulative loading where loads, each individually below the threshold that damages the atomic structure, unite. Such circumstances arise when a light load supported on a jammed particle then combines with additional loads from other stress-raising incidents. These incidents include impact loads from misaligned shafts, tightened clearances from overheated bearings, forces from out-of-balance masses, and sudden operator-induced overload. All these stress events are random. They might happen, or they may not happen, at the same time and place as a contaminant particle is jammed into the surface of a roller. Whether they combine together to produce a sufficiently high stress to create new cracks, or they happen on already damaged locations where lesser loads will continue the damage, are matters of probability. The failure of a roller bearing is now directly related to the chance of failure inherent in the processes selected to maintain and operate equipment.

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*FAG OEM und Handel AG, ‘Rolling Bearing Damage – recognition of damage and bearing inspection’, Publication WL82102/2EA/96/6/96
### Causes of Atomic and Microstructure Stress

<table>
<thead>
<tr>
<th>Factors that cause Atomic or Microstructure Failure</th>
<th>Component Manufacturing Events</th>
<th>Component Operational Stress Events (Horizontal, Vertical, Axial)</th>
<th>Component Environmental Events / Conditions</th>
<th>Component Life Cycle Situations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compresion Flaw overload</td>
<td>Metallographic error</td>
<td>Pressure</td>
<td>Electrolytic discharge</td>
<td>Conception</td>
</tr>
<tr>
<td>Sudden stress overload</td>
<td>Formulation error</td>
<td>Sudden thermal stress</td>
<td>Thermal high</td>
<td>Lead</td>
</tr>
<tr>
<td>Shear Stress overload</td>
<td>Fracture stress</td>
<td>Interference line stress</td>
<td>High stress</td>
<td>Project management</td>
</tr>
<tr>
<td>Cyclic Stress overload</td>
<td>Fracture stress</td>
<td>Interference line stress</td>
<td>High stress</td>
<td>Project management</td>
</tr>
<tr>
<td>Sheet Stress overload</td>
<td>Fracture stress</td>
<td>Interference line stress</td>
<td>High stress</td>
<td>Project management</td>
</tr>
<tr>
<td>Punch flaws in metal structure</td>
<td>Fracture stress</td>
<td>Interference line stress</td>
<td>High stress</td>
<td>Project management</td>
</tr>
<tr>
<td>Hole in metal structure</td>
<td>Fracture stress</td>
<td>Interference line stress</td>
<td>High stress</td>
<td>Project management</td>
</tr>
<tr>
<td>Crack in metal structure</td>
<td>Fracture stress</td>
<td>Interference line stress</td>
<td>High stress</td>
<td>Project management</td>
</tr>
<tr>
<td>Material fatigue from metal structure</td>
<td>Fracture stress</td>
<td>Interference line stress</td>
<td>High stress</td>
<td>Project management</td>
</tr>
<tr>
<td>Void in metal structure</td>
<td>Fracture stress</td>
<td>Interference line stress</td>
<td>High stress</td>
<td>Project management</td>
</tr>
<tr>
<td>Welding at metal structure</td>
<td>Fracture stress</td>
<td>Interference line stress</td>
<td>High stress</td>
<td>Project management</td>
</tr>
<tr>
<td>Electromagnetic welding</td>
<td>Fracture stress</td>
<td>Interference line stress</td>
<td>High stress</td>
<td>Project management</td>
</tr>
<tr>
<td>Chemical reaction</td>
<td>Fracture stress</td>
<td>Interference line stress</td>
<td>High stress</td>
<td>Project management</td>
</tr>
<tr>
<td>Crystal lattice stress</td>
<td>Fracture stress</td>
<td>Interference line stress</td>
<td>High stress</td>
<td>Project management</td>
</tr>
<tr>
<td>Depositional stress</td>
<td>Fracture stress</td>
<td>Interference line stress</td>
<td>High stress</td>
<td>Project management</td>
</tr>
</tbody>
</table>

Operating stresses work on the atomic and microstructure of a material. The loads and forces of operation are absorbed by the atoms and crystals of the material of construction. If the stresses in the atomic bonds are too great they break the bond. Where operating stresses are beyond the capacity of the material structure the structure fails. Once enough stress failures accumulate the part breaks and then a machine stops.

The materials of which parts are made do not know what causes them stress. They simply react to the stress experienced. If the stress is beyond their material capacity, they deform as the atomic structure collapses. All materials of construction suffer structural damage at the atomic level when concentrated overload stress occurs. The greatest stress occurs when the load is localised to a very small area on a part. Once a failure site starts in the atomic matrix it progresses and grows larger whenever sufficient stress is present. The stress to propagate a failure is significantly less than the stress needed to generate the failure. Any load applied at a highly localised stress concentration point is multiplied by orders of magnitude. Once the material of construction is damaged even normal operating loads maybe enough to extend the damage to the point of failure.

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8 Juvinall, R. C., Engineering Considerations of Stress, Strain and Strength, McGraw-Hill, 1967
Know the Limits of Your Parts

This graph is called a stress-life cycle curve. A great deal of fatigue load testing, where the load cycles in one direction and is then reversed, has been done with a wide range of metals. These tests produce graphs of tensile strength verses number of cycles to failure. From these tests graphs of tensile strength verses number of cycles to failure have been developed. An example of one for wrought (worked) steel commonly used in many industries is shown in the Figure. It helps us to understand how much load a material can repeatable take and still survive. Under loads at 90% its maximum yield strength it will last 10,000 cycles. Loads about 50% of maximum yield get 1,000,000 cycles before failure. But if loads are below half its yield strength, it has an indefinite life. Note that not all metals have a defined fatigue limit like steels. Some metals continue to degrade throughout use and parts made of such materials need replacement well before the part approaches fatigue failure. The replacement of parts before failure from operational age and use is known as preventive maintenance.

The vertical scale on this log-log plot shows the applied stresses as a proportion of the steel’s ultimate tensile stress ‘Su’ while the horizontal scale is the number of stress cycles to failure. The left hand sloping line tells us that a steel part put under high cyclic loads producing stresses in high proportion to its ultimate tensile stress will fail after a given number of cycles. Whereas the right hand side of the curve indicates that if cyclic stresses are maintained below a definable limit the part will have infinite life. The curve also tells us that a steel part made of this metal will fail if it has just one load cycle with a stress greater than its ultimate tensile strength. (Like when a small bolt snaps-off if over-tightened) It will also fail in less than several thousand cycles if the imposed stresses are 90% or more of the tensile strength. But if the stresses are kept below half of the tensile strength it will never fatigue. As a rough guide, the fatigue limit is usually about 40% of the tensile strength. In principle, components designed so that the applied stresses do not exceed this level should not fail in service. Note that Curve B advises us that not all metals have a fatigue limit.
Have you ever bent a metal wire back and forth until it breaks from being worked? If you have then you were performing a stress life-cycle test. The wire does not last long when bent severely one way and then back the other way. Each bend is an overstress, and eventually the overstress damage accumulates and the wire fatigues and fails.

Owing to the statistical nature of the failure, several specimens have to be tested at each stress level. Some materials, notably low-carbon steels, exhibit a flattening off at a particular stress level as at (A) in the figure which is referred to as the fatigue limit. The difficulty is a localised stress concentration may be present or introduced during service which leads to initiation, despite the design stress being normally below the ‘safe’ limit. Most materials, however, exhibit a continually falling curve as at (B) and the usual indicator of fatigue strength is to quote the stress below which failure will not be expected in less than a given number of cycles which is referred to as the endurance limit.

Although fatigue data may be determined for different materials it is the shape of a component and the level of applied stress which dictate whether a fatigue failure is to be expected under particular service conditions. Surface condition is also important to prevent crack initiation. Often complete components or assemblies, e.g. railway bogie frames or aircraft fuselage, will be tested by subjecting them to an accelerated loading spectrum reproducing what they are likely to experience over their entire service lifetime.

Operating Stresses Cause Failure


The diagram shows how three different operating methods stress a dragline boom. The way a machine is used affects its rate of failure. The Table provides a measure of the operating impact of each practice. Method B causes a lot of damage – the loads are higher and the fatigue from stress cycling accumulates faster. Method A is slower and method C is most gentle. ‘B’ has an expected 5 failures a year and ‘C’ only 2 a year. But which operating practice is best for the business?
To make the necessary assessment, we need to know the DAFT Costs for each option. Then we can see if the extra throughput from ‘B’ actually produces a lower unit cost product. If it does, then ‘B’ should become the standard way to operate. But if it does not, then Method B must be abandoned.

Recall that the unit cost equation is,

\[
\text{Unit Cost} = \frac{\text{Total Cost of Production}}{\text{Total Throughput}}.
\]

If the DAFT Costs of the extra 3 failures from using Method B, cost more than the extra 22 million units produced from Method C, the company will be losing money. Until we can do an economic model of the different ways to operate the equipment it is not possible to say which of Methods A, B or C is the best one to use for the business.

We know that parts fail from being overstressed. This overstress is imposed on the part. Each overstress takes away a portion of the part’s strength. When enough overstress accumulates, or there is one large overload incident, the part suddenly fails. To overload a part is a choice that eventually leads to failure. Overloading is a mistake that robs our machines of a long, trouble-free service life.
The stresses that parts experience result from their situation and circumstances. Overstress or fatigue a part and you damage it. The damage stays in the part, continually weakening it. Where local operating conditions attacks the part, for example from corrosion or erosion, the two factors – overload and weakening – act together to compound the rate of failure.

Overstressed parts fail. The imposed overstress comes from external incidents where an action is done to overload a parts microstructure. Each overstress takes away a portion of the part’s strength. When enough overstress accumulates (fatigue), or there is one large load incident (overload), the part suddenly fails.

Excessive stresses lower the capacity of materials of construction to accommodate future overloads. A portion of the material strength is lost with each high stress incident until a last high stress incident occurs which finally fails the part. These excessive stresses are not necessarily the fault of poor operating practices. In fact they are unlikely to only be due to operator abuse. They are more likely to be due to the acceptance of bad engineering and maintenance quality standards that increase the probability of failure in stressful situations.

Wear-out failures are any failure mechanism that result from parts weakening with age and usage. Included are processes involving material fatigue, wearing between surfaces/substances in contact, corrosion, degrading insulation, and wear-out in light bulbs and fluorescent tubes. Initially the strength is adequate for the applied load, but over time the strength decreases. In every case the average strength value falls and the spread of strength distribution widens. This makes it very difficult to provide accurate predictions of operating life for such items.

The Figure highlights the failure prediction dilemma—the timing and severity of overload incidents is unknowable. They may happen and they may not happen. It seems a matter of luck and chance whether parts are exposed to high risk situations that could cause them to fail. When
they are overstressed the materials of construction degrade and fatigue. Eventually an incident occurs that makes the item break.

Nothing lasts forever. In time all parts will need to be replaced or a new machine purchased. Preventive Maintenance is done to replace parts before they fail from usage or age. Maintainers try to estimate the safe period before failure and renew parts before the risk gets too high. Overhauls are undertaken to replace aged parts. Eventually the overhauls do not regain much more working life and the entire asset needs to be renewed with a complete replacement.

It is important that companies put money into their capital budgets to buy new assets to replace those that are too tired and fatigues from fair wear and use or damaged and destroyed before their full term from abuse.

Degradation Cycle of Machines and Parts

The degradation cycle shows the failure sequence for parts. Under abnormal operation equipment parts can start to fail. They go through the recognisable stages of degradation shown in the Figure. This degradation cycle is the basis of condition monitoring, which is also known as Predictive Maintenance. The degradation curve is useful in explaining why and when to use condition monitoring. Knowing that many mechanical parts show evidence of developing failure it is sensible to inspect them at regular time intervals for signs of approaching failure. Once you select an appropriate technology that detects and measures the degradation, the part’s condition can be trended and the impending failure monitored until it is time to make a repair.

The point at which degradation is first possible to detect is known as the potential failure, ‘P’, point. The point at which failure has progressed beyond salvage is the functional failure, ‘F’ point. At this stage the equipment cannot perform its duty, though it may still be operating. We must condition monitor frequently enough to detect the onset of failure (the ‘P’ point) so we have time to address the functional failure before it happens.
Some parts fail without exhibiting warning signs of a coming disaster. They show no evidence of degradation, there is just sudden catastrophic failure. In such cases, all we see is the sudden death of the part. This commonly happens to electronic parts. It is worth noting that almost all failures, even to electrical and electronic parts, are ultimately mechanical, contaminant or over-temperature related. Largely we can prevent those situations.

**Roller Bearing Defect Severity**

An example of using the degrading curve is when monitoring the remaining life of roller bearings. There are defined zones of health as the bearing degrades.

**Stage 1.** Earliest detectable indication of bearing failure using vibration analysis. Signals appear in the ultrasonic frequency bands around 250 KHz to 350 KHz. At this point, there is approximately 10 to 20 percent remaining bearing life.

**Stage 2.** Bearing failure begins to "ring" at its natural frequency, (500 to 2,000 Hz) signal appears at the first harmonic bearing frequency. Five to 10 percent remaining bearing life.

**Stage 3.** Bearing failure harmonics of the fundamental frequency are now apparent. Defects in the inner and outer race are now apparent and visible on vibration analysis of the noise signal. Temperature increase is now apparent. One to five percent of remaining bearing life.

**Stage 4.** Bearing failure is indicated by high vibration. The fundamental and harmonics begin to actually decrease, random ultrasonic noise greatly increases, temperatures increase quickly. Remaining life one hour to one percent.

The problem with condition monitoring is that we have not actually stopped the cause of the failure. We simply detect an imminent failure before it happens and turn a breakdown into a planned maintenance job. As good as that is in reducing production costs and downtime, the failure causes remain and the failure will recur.
Establish Equipment Condition Monitoring

Since we can see the condition of our parts degrading, we only need to monitor for the evidence that things are deteriorating. Once the condition has got close to the functional failure point on the degradation curve it must be changed. Usually the job can be planned and prepared ahead of time so that the work can be done during a planned production outage.

Condition monitoring can detect an impending failure. It spots tell-tale signs of degradation and warns when to do a repair. Instead of a breakdown from a failure, the equipment repair becomes a planned maintenance task. From being a breakdown, it becomes a shutdown. Planned maintenance allows maintenance work to be done cheaper than breakdown repair because the repair time is reduced through good preparation and the production stoppage is scheduled at a convenient time to minimise production impact.

As part of a condition monitoring strategy you will need to develop a table such as that in the Figure. This table identifies which machines will be condition monitored, with what techniques and for what purpose. The strategy then becomes part of your annual maintenance management plans and is funded from your annual maintenance budget.

Condition monitoring saves companies from breakdowns, but it does not stop failure initiation. With condition monitoring, organisations may not suffer an equipment breakdown, but they will still have to stop and do a repair. That work would not be necessary if they prevented failure initiating defects from starting.
The mechanisms of failure caused by stressing components has become known as the Physics of Failure (PoF).

It recognises the influences and effects of the Physics of Failure on parts. The parts are modelled with Finite Element Analysis (or prototype tested in a laboratory), and their behaviours analysed under varying operating load conditions. The modelling identifies likely life cycle performance in those situations. The results warn of the design limit and operating envelope of the materials-of-construction. The tests indicate what loads equipment parts can take before failing. During operation we must ensure parts never get loaded and stressed to those levels, or that they are allowed to degrade to the point they cannot take the loads. It is the role of maintenance management and reliability engineering to ensure parts do not fail and machines do not stop.

We know the factors that cause our parts and equipment to fail – sudden excess stress and accumulated stress. During the design of plant and equipment we apply the knowledge of the Physics of Failure to select the right materials and designs that deliver affordable reliability during operating life. The design stress tolerances set the limit of a part’s allowable distortion. To maximise reliability we first must keep the parts in good condition to take the service loads. Secondly we must ensure the equipment is operated so that loads are kept well within the design envelope. If the loads applied to a part deforms it so far that it forces the atomic structure to collapse, there will be a failure. It may be immediate if it is an overload, or it will be eventually if it is fatigue. If you want highly reliable equipment don’t let your machine’s parts get tired, or twisted out-of-shape.

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9 Pecht, Michael., ‘Why the traditional reliability prediction models do not work – is there an alternative?’, CALCE Electronic Product and Systems Center of the University of Maryland, College Park, MD, 20742, USA.
Failure Mode and Effects Analysis
Definitions

- A failure is any unwanted or disappointing behaviour of a product.

- A failure mode is the effect by which a failure is observed. Failure modes can be electrical (open or short circuit, stuck at high), physical (loss of speed, excessive noise), or functional (loss of power gain, communication loss, high error level).

- Failure mechanism refers to the processes by which the failure modes are induced. It includes physical, mechanical, electrical, chemical, or other processes and their combinations. Knowledge of failure mechanism provides insight into the conditions that precipitate failures.

- A failure site describes the physical location where the failure mechanism is observed to occur, and is often the location of the highest stresses and lowest strengths.

We can foretell what parts are going to cause trouble by doing experiments, from conducting tests and by using past failure history of similar parts. If we can predict what will go wrong, and the conditions that will cause it to happen, we can design maintenance and operational loading strategies to give maximum part life.

FMEA is both a qualitative and quantitative technique to identify how equipment can fail in order to design-out a failure, or to identify and apply suitable maintenance practices to correct a developing problem before it leads to a failure.

This is a methodology for analysing potential reliability problems early in the development cycle where it is easier to take actions to overcome these issues, thereby enhancing reliability through design. FMEA identifies potential failure modes, determine their effect on the operation of the plant, and identify actions to mitigate the failures. A crucial step is anticipating what might go wrong with a process. While anticipating every failure mode is not possible, the development team should formulate as extensive a list of potential failure modes as possible.

The early and consistent use of FMEAs in the design process allows the design-out of failures and production of reliable, safe, and easily operable plant and equipment. FMEAs also capture historical information for use in future improvements. Initially a high-level Failure Mode and Effect Analysis (FMEA) is conducted at the equipment and assembly level using the production process maps.

A small team of people knowledgeable in the design, use and maintenance of the equipment assemble together to work through the maps, asking what causes each operating equipment item to fail, including identifying failures from possible combined causes. The size and composition of the team is not critical as long as it contains the necessary design, operation and maintenance knowledge and expertise covering the equipment being reviewed. Ideally, Operations and Maintenance shopfloor level supervisors are in the review team so they understand the purpose of the review, and can later support the efforts needed to instigate and perform the risk control activities that will arise.
Example of an expanded list of failure modes

<table>
<thead>
<tr>
<th></th>
<th>Failure Mode</th>
<th></th>
<th>Failure Mode</th>
<th></th>
<th>Failure Mode</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cracked/fractures</td>
<td>11</td>
<td>Fails to stop</td>
<td>21</td>
<td>Binding/jamming</td>
<td>31</td>
</tr>
<tr>
<td>2</td>
<td>Distorted</td>
<td>12</td>
<td>Fails to start</td>
<td>22</td>
<td>Loose</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>Undersize</td>
<td>13</td>
<td>Corroded</td>
<td>23</td>
<td>Incorrect adjustment</td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>Oversize</td>
<td>14</td>
<td>Contaminated</td>
<td>24</td>
<td>Seized</td>
<td>34</td>
</tr>
<tr>
<td>5</td>
<td>Fails to open</td>
<td>15</td>
<td>Intermittent operation</td>
<td>25</td>
<td>Worn</td>
<td>35</td>
</tr>
<tr>
<td>6</td>
<td>Fails to close</td>
<td>16</td>
<td>Open circuit</td>
<td>26</td>
<td>Sticking</td>
<td>36</td>
</tr>
<tr>
<td>7</td>
<td>Fails open</td>
<td>17</td>
<td>Short circuit</td>
<td>27</td>
<td>Overheated</td>
<td>37</td>
</tr>
<tr>
<td>8</td>
<td>Fails Closed</td>
<td>18</td>
<td>Out of tolerance (drifted)</td>
<td>28</td>
<td>False response</td>
<td>38</td>
</tr>
<tr>
<td>9</td>
<td>Internal leakage</td>
<td>19</td>
<td>Fails to operate</td>
<td>29</td>
<td>Displaced</td>
<td>39</td>
</tr>
<tr>
<td>10</td>
<td>External leakage</td>
<td>20</td>
<td>Operates prematurely</td>
<td>30</td>
<td>Delayed operation</td>
<td>40</td>
</tr>
</tbody>
</table>

Source Table 2 BS 5760

The normal practice in an FMEA is for a team of specialist in the equipment’s design, use and maintenance to conduct a design review. The team looks at each equipment asset to find and record all the ways in which it can fail. They assess the effect of each failure on the equipment’s ability to continue in operation. For each failure mode, the team suggests risk mitigation. These include redesign, preventive and predictive maintenance, improved work quality control or, in low consequence situations, to allow the failure to happen. Once the strategies to control or prevent the failure are selected, another review is made of how truly useful they will be in reducing stress levels significantly enough to stop failure. An important consideration during the FMEA is to identify when two or more parts could fail in association. The combined failures of multiple parts may lead to greater catastrophe than one part failing alone. These combined failures also need to be considered and controlled.

When FMEA is used during design, the principle is to consider each mode of failure of each part and determine the knock-on and system-wide effects of each failure mode in-turn. The learning from the FMEA is put back into the design and the equipment is improved, or specific risk management requirements are placed on operational and maintenance groups when the equipment is in service. It is an iterative process performed regularly during the design. When FMEA is used on existing operating plant and equipment many modes of failure are already known. Modes that are unlikely to occur in the operation are checked for their DAFT Costs and then a decision is made as to whether or not they will be pursued.
Failure Mode Effects Analysis

<table>
<thead>
<tr>
<th>Failure</th>
<th>Failure Mode</th>
<th>Failure Mechanism</th>
<th>Failure Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car does not start</td>
<td>Starter Motor does not run</td>
<td>Corroded relay contacts</td>
<td>Main contact of starter relay</td>
</tr>
<tr>
<td>Toy has faded colour</td>
<td>Colour changes from red to pink</td>
<td>Accumulation of high UV dose</td>
<td>Red plastic leg</td>
</tr>
<tr>
<td>Hard disk failure</td>
<td>Computer has no access to hard disk</td>
<td>Hard disk address is 11 instead of 12</td>
<td>Line 87 in the hard disk driver software</td>
</tr>
</tbody>
</table>

Once this is known we put strategies and practices into place to:
1) Design-out the failure, 2) prevent the failure, 3) monitor the failure mode 4) replace before failure 5) prevent the conditions.

FMEA is also useful when doing root cause failure analysis to investigate how parts in equipment can fail. The evidence from the failure incident is used to confirm the failure mode(s) and cause.

Failure Mode and Effects Analysis (FMEA)

![Failure Mode and Effects Analysis (FMEA) Diagram]

- 82 -
This is an overview of the FMEA team review process. It is a logical progression through each assembly and sub-assembly in an item of plant asking the question, “What can go wrong in its operation?” The team of subject matter experts identify the causes and then agree to the operating and maintenance actions to be performed to prevent a failure. These actions become maintenance and operating tasks.

FMEA leads to a very clear and structured analysis of failure cause and consequences so problems can be addressed and mitigated in a suitable cost-effective way.

Activity 2 – Failure Mode and Effects Analysis (FMEA)

Do a FMEA for a component in an item of machinery.
5. Activity 2A – FMEA at System Level

At the system level the principle is to consider during the design phase each failure mode of every equipment of a process and to determine the effects on process operation of each failure mode in-turn.

When used in the design phase the learning from the FMEA is taken back into the design and the equipment is improved. It is an iterative process performed regularly during the design. In an FMECA the failures identified in the FMEA are classified by their severity (criticality).

When used during the operational phase the FMEA allows selection of the operating and maintenance requirements to identify failure causes and correct them when observed, and to develop preventive strategy and means to stop them occurring in the first place.

Methodology:

1. Specify the purpose of the FMEA. It can be for reasons of safety, plant availability, repair cost, mission success, etc so attendees’ viewpoints are aligned.
2. Provide all available design data and operating data to allow development of a full understanding of the equipment design and its service.
3. Develop a system functional block diagram and, if possible, the reliability block diagram, to promote complete analysis.
4. Prepare the worksheet listing assemblies and components.
5. Assemble a cross-functional team to conduct the FMEA.

Activity:

Conduct an FMEA on the electric motor arrangement below using the FMEA worksheet over the page and develop ideas for improving its reliability.
Specify System ________________________
Equipment ________________________
Drawing ________________________

### FAILURE MODE and EFFECTS ANALYSIS WORKSHEET

<table>
<thead>
<tr>
<th>ID No</th>
<th>Item Description</th>
<th>Functions of Item</th>
<th>Function Failure Mode</th>
<th>Failure Mode Causes</th>
<th>Failure Effect/Damages</th>
<th>Symptoms of Failure Mode</th>
<th>Failure Mode Detection Method</th>
<th>Rectification on Failure</th>
<th>Action to Prevent Failure Causes</th>
</tr>
</thead>
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</tbody>
</table>

Date ________________
Sheet _________ of _________
Complied By ______________________
Approved ______________________

ID No: 85
CM Technique

The Item
Its Neighbours
Whole System
6. Activity 2B – FMEA at Component Level

At the component level the principle is to consider during the design each failure mode of every component of an equipment item and to determine the effects on the equipment operation of each failure mode in-turn.

When used in the design phase the learning from the FMEA is taken back into the design and the equipment is improved. It is an iterative process performed regularly during the design. In an FMECA the failures identified in the FMEA are classified by their severity (criticality).

When used during the operational phase the FMEA allows selection of the operating and maintenance requirements to identify failure causes and correct them when observed, and to develop preventive strategy and means to stop them occurring in the first place.

Methodology:

1. Specify the purpose of the FMEA. It can be for reasons of safety, plant availability, repair cost, mission success, etc so attendees’ viewpoints are aligned.
2. Provide all available design data and operating data to allow development of a full understanding of the equipment design and its service.
3. Develop a system functional block diagram and, if possible, the reliability block diagram, to promote complete analysis.
4. Prepare the worksheet listing assemblies and components.
5. Assemble a cross-functional team to conduct the FMEA.

Group Activity:

Conduct an FMEA on the electric motor bearing and housing arrangement below using the FMEA worksheet over the page and develop ideas for improving its reliability.

AC Electric Motor Bearing Arrangement
<table>
<thead>
<tr>
<th>ID No</th>
<th>Item Description</th>
<th>Functions of Item</th>
<th>Function Failure Mode</th>
<th>Failure Mode Causes</th>
<th>Failure Effect Damages/Costs/Losses/Safety</th>
<th>Symptoms of Failure Mode</th>
<th>Failure Mode Detection Method</th>
<th>Rectification on Failure</th>
<th>Action to Prevent Failure Causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inner bearing cap</td>
<td>Locate outer bearing ring</td>
<td>1) Cap misaligned</td>
<td>Not located properly</td>
<td>Incorrectly fitted</td>
<td>1) Outer ring moves axially 2) Shaft moves axially</td>
<td>1) Eventual bearing failure 2) Eventual winding failure</td>
<td>1) Noise 2) Arcing</td>
<td>1) Vibration analysis 2) Winding current/voltage</td>
</tr>
<tr>
<td></td>
<td>2) Cap loose</td>
<td>Not firmly installed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Position grease against bearing
Restrict grease entry into motor
That’s our hour Joe.

WHAT!?, … You are kidding me, … aren’t you?

Already, … where did the time go? Before you leave, I need to set you another question: How do we predict the day an item of equipment will fail?

No, it can be done. See what you can find out before tomorrow.

Good morning Ted. What did you find out about predicting an equipment’s failure date?

I told Bill that you were the right man for this job. Reliability engineering is all about predicting risk and the likelihood of equipment and part failure. Can you imagine how useful it is to maintainers and operators to know the day a machine will fail?

It means we would never have a failure.

Good morning Joe.

I thought you were crazy when you asked me that question yesterday. After tea last night I searched the Web for ‘predicting equipment failure’ and came across lots of sites explaining reliability engineering.

The next morning …
Reliability of Parts and Systems of Parts

The aim in reliability engineering is to draw the likely reliability curve for each of these items and 'systems'.

The reliability curve for a part is like the curve on the bottom of the slide – it is called a 'hazard curve' for an individual part (There is a different curve for a machine i.e. an assembly of parts). If we can estimate the dates between which it will fail we can change the part with a new one beforehand.

For the parts in the slide we do not have any real data, but using our experiences we can visualise the shape of the probability of failure curve for the items shown. For example the likelihood of the glasses failing due to internal faults is zero. But the likelihood of them failing due to mishandling is real, and people experience it when they break a glass.

The same analogy can be applied to all the items shown in the slide to show that probability of failure curves can be drawn to reflect the chance of real-world failure or equipment parts.
What is the Reliability of this Drinking Glass?
In other words: ‘What’s the chance it will hold water next time you use it?’

What can cause this glass to break?

- It can be dropped, for example -
  1. slip from your hand
  2. fall off a tray
  3. slip out of a bag or carry box
- It can be knocked,
  1. hit by another glass
  2. clanked when stacked on each other
  3. hit by an object, like a plate or bottle
- It can be crushed,
  1. jammed hard between two objects
  2. stepped on
  3. squashed under a too heavy object
- It can be temperature shocked,
  1. in the dish washer
  2. during washing-up
- Mistreated,
  1. it can be thrown in anger
  2. it can be smashed intentionally
- Latent damage
  1. scratched and weakened to later fail more easily
  2. chipped and weakened to later fail more easily

These many ways for the glass to break (the failure mode), are called ‘failure mechanisms’.

There are 15 causes of drinking glass breakage shown in the list. I’m sure that you can come up with more causes.

How many times a year does a glass get broken in your place? People have told me from one a year in their place and others up to five a year at their place. In my house about two glasses a year get broken. Mostly by me, because I wash the plates and glasses after meals.

If ‘reliability’ is the chance that a thing will work properly, we can ask what will stop the glass from ‘working properly’. There are numerous reasons that a glass will break (the ‘failure mechanisms’), many of them are listed in the table on the slide. Each cause of failure can happen to a glass if the particular circumstances arise. This means the ‘chance’ of the glass breaking depends on the frequency, or how often, that ‘bad’ circumstances arise. But before the glass breaks it needs to be both put in danger (the opportunity) AND enough force applied (the failure mechanism) to break it.

Most often people say ‘failure modes’ rather than ‘mechanisms’.
We can estimate the chance of breaking a glass in a year, i.e. the failure rate, by analysing the history of the glass. Let’s say it came from a manufacturing run of a million drinking glasses which were sold through shops around the world in a carrier packs of twelve glasses. Each pack went to a household, one of them was your place and another was my place. That means 83,333 households had a set of glasses and put them on their shelf to use.

At the beginning only a few of the many causes of glass breakage can happen. When a new drinking glass is taken out of the glass-carrier and put on a shelf it is possible to drop it. As the glass is first moved into place on the shelf it is possible for it to hit something else on the shelf. It is reasonable to expect breakages will begin on the day of purchase (some glasses will be broken when first putting them on a shelf, though not many because people will be careful with new glasses—maybe only 10 or 20 in 83,333 households) and continuing for as long as the glasses are used. So the chance of the glass being broken at the start of its ‘working’ life is not zero because in some of the 83,333 households a glass will be broken when first stored. Over time more opportunities for failure arise. As the glass is used for different functions, family get-togethers, celebrations, special occasions, etc opportunities constantly arise for an accident or problem to occur that results in a broken glass. With enough time the causes repeat endlessly.

Hence we can draw the intrinsic rate of failure for a million identical glasses, or the hazard curve for a glass, as a straight line curving up from the day the glass is purchased and levelling out after about 18to 24 months as the annual cycle of glass usage stabilises. The number failing each day is unknown, but our life experience suggests that an average of one or two glasses broken every year in a household is a believable situation. Hence if 1,000,000 glasses were sold, then for household that break one glass a year the hazard curve for the glasses would be a straight line at 0.083 probability per year. For those that break two a year the line will be at 0.167. You can see on the slide how the annual failure rate of 0.167 was calculated for the group of 1,000,000 glasses. For your 12 glasses at my home the failure rate is 0.167 ÷ 83,333 = 0.000002, or two in a million.
If you wanted to reduce the number of drinking glasses broken in a year what can you do?

**Stop Breakage = Remove Failure Causes**

Once the causes of failure are known they can be targeted with solutions to prevent them.

Glass breakages can be stopped by a **design change**, such as replacing glass with plastic, by changing the glass design to one that is stronger, or using a glass of a design that prevents a failure cause arising. **Procedural changes** can be made such as carrying glasses in locating trays. Improved **instructions with training** can be used to up-skill people and give them specialised knowledge and techniques.

Once failure causes are removed there will be fewer failures and the failure rate curve falls. With fewer failures less money is lost to DAFT Costs. The maintenance costs fall, the operating profit improves and people win back time to spend on improving the operation further.
Reliability = Remove Likelihood of Failure

For each failure mode of a part, the failure curves for it can be developed. Data is collected for each type of part from many applications. For each failure mode, the life of the parts is measured and the numbers of parts failing from that mode in each time period is charted. The sum of the likelihoods for each mode becomes the total chance of the part failing.

The curve for the total each part’s failure modes shows the chance of the part failing in a particular time period due to that failure mode.

To reduce the chance of failure, it is necessary to remove the causes of failure. As each cause is removed, there are fewer opportunities for the part to fail. Because the causes of failure are not about there is less chance to fail and on average the item lasts longer between stoppages.

The story is always the same and applies to every part and every assembly in a machine—to improve equipment reliability remove the failure causes so that there are no reasons for the parts to fail and the equipment to stop.
Individual Parts Reliability Curves

The Six Failure Curves and the Percentage Of Component (i.e. parts) Types They Apply Too.

Total 10% 25%  Total 90% 75%

Age-Based Failures

Random Failures

Because failure is probabilistic for 75% - 90% of parts, i.e. their failure is a chance event, this makes replacement of those parts on a certain date totally pointless. If the part did not show evidence of failure then it could have remained in operation for a very long time. You spent money unnecessarily replacing a part that had nothing wrong with it.

In the 1960’s the aircraft industry needed ways to lower maintenance costs. Typically 2,000,000 man hours were required every 20,000 hours of flying time to overhaul jet engines. Maintenance was based on the ‘bath tub’ curve model of component life (Pattern A), which was the industry-wide view of maintenance at the time. The practice was to replace parts after sometime because the ‘model’ assumed all parts aged and would fail after a certain time.

A 1978 study by Nolan and Heap identified that component failure was probabilistic and six failure patterns existed for aircraft components (parts). The traditional ‘bathtub’ curve accounted for only 4% of the failures. The fascinating discovery was that 11% of failures were age related; the remaining 89% were random. This meant that age based maintenance was pointless in most cases. From their work Nolan and Heap coined the phrase – reliability centred maintenance (RCM) – which focused on determining the probability of component failure and matched maintenance inspections to the component’s likelihood of failure.

RCM recognised that it was not possible to eliminate failure through the maintenance effort. Rather failure had to be designed-out or deterioration monitored. RCM achieved significant improvement in reliability and reduced maintenance costs by better design decisions. The following results that have been documented:

Reductions in the amount of Scheduled Maintenance Labour Hours of 87%
Reductions in Total Maintenance Labour Hours of up to 29%
Reductions in Maintenance Materials costs of up to 64%
Improvements in Equipment Availability of up to 15%
Improvements in Equipment Reliability of up to 100%

Clearly RCM is a valuable design tool to give substantial improvements in reliability.
Research by the US navy after the Nolan and Heap study confirmed their findings. There was some variation in percentages due to the different type of equipment and components, the marine operating environment and stringent US naval commissioning and maintenance practices.

The Pattern ‘F’ curve represented 68% of aircraft component failures. It means there is a high ‘infant mortality’ rate. The implication being that a great proportion of equipment suffers early failure from poor quality work or induced problems. The problems of quality workmanship are reduced by thorough planning in which detailed information and procedures are made available to the maintainers. To decrease the chance of ‘infant mortality’ further it is necessary to train the technicians in precision maintenance practices.

Reliability Properties for Systems

• Series Systems

$$R_{\text{system}} = R_1 \times R_2 \times R_3 \ldots R_n$$

$$R = 0.95 \times 0.95 = 0.9025$$

• Parallel Systems

$$R_{\text{system}} = 1 - [(1 - R_1)(1 - R_2)(1 - R_3)\ldots(1 - R_n)]$$

(only fully active)

$$R = 1 - [(1 - 0.6)(1 - 0.6)] = 0.84$$

The mathematics can be difficult. But you need to know that such mathematics exists and be able to use the principles to optimise maintenance.

When parts are used to make a machine, or machines are used to make processes, they can be grouped either in a series or in a parallel arrangement.

The system reliability performance can be calculated from the component reliability performance using the mathematics of probability and statistics. The component reliability is determined from the components failure history.

The reliability of a series system is the multiplication of the reliability (chance of success) of its components using the equation $$R_{\text{system}} = R_1 \times R_2 \times R_3 \ldots R_n$$.

Calculation of the reliability of a parallel arrangement depends on how the arrangement is configured to work. The equation in the slide applies only to a ‘fully active’ state, which means any of the items can do the complete duty by itself. This is what is done for the flying systems in commercial aircraft. They have multiple independent ways to fly the plane in case one system fails. There are other equations that apply where 2 out of 3, or 3 out of 4 items in a parallel system must operate for the system to deliver the required duty.
The final reliability of a series system is always less than its least reliable component. While the reliability of a parallel arrangement is always higher than that of its most reliable item.

**Reliability Properties for Series Systems**

\[ R_{\text{system}} = R_1 \times R_2 \times \ldots R_n \]

**Properties of Series Systems**

1. **The reliability of a series system can be no higher than the least reliable component.**

   The reliability of a series of parts (this is a machine – a series of parts working together) cannot be higher than the reliability of its least reliable part. Say the reliability of each part in a two component system was 0.9 and 0.8. The series reliability would be 0.9 x 0.8 = 0.72, which is less than the reliability of the least reliable item. Even if work was done to lift the 0.8 reliability up to 0.9, the best the system reliability can then be is 0.9 x 0.9 = 0.81.

2. **Add ‘k’ items into a series system of items, and the probability of failure of all items in the series must fall an equal proportion to maintain the original system reliability.**

   Say one item is added to a system of two. Each part is of reliability 0.9. The reliability with two components was originally 0.9 x 0.9 = 0.81, and with three it is 0.9 x 0.9 x 0.9 = 0.729. To return the new series to 0.81 reliability requires that all three items have a higher reliability, i.e. 0.932 x 0.932 x 0.932 = 0.81. Each item’s reliability must now rise 3.6% in order for the system to be as reliable as it was with only two components.

3. **An equal rise in reliability of all items in a series causes a larger rise in system reliability.**

   Say a system-wide change was made to a three item system such that reliability of each item rose from 0.932 to 0.95. This is a 1.9% individual improvement. The system reliability raises from 0.932 x 0.932 x 0.932 = 0.81, to 0.95 x 0.95 x 0.95 = 0.86, a 5.8% improvement.

**Implications for Equipment made of Series Systems**

1. System-wide improvements lift reliability higher than local improvements. This is why SOP’s, training and up-skilling pay-off.
2. Improve the least reliable parts of the least reliable equipment first.
3. Carry spares for series systems and keep the reliability of the spares high.
4. Standardise components so fewer spares are needed.
5. Removing failure modes lifts system reliability. This is why Root Cause Failure Analysis (RCFA) and Failure Mode and Effects Analysis (FMEA) pay off.
6. Provide pseudo-parallel equipment by providing tie-in locations for emergency equipment.
7. Simplify, simplify, simplify – fewer components means higher reliability.

A series arrangement has the three very important series reliability properties described below.

1. **The reliability of a series system is no more reliable than its least reliable component.**

2. **Add ‘k’ items into a series system of items, and the probability of failure of all items in the series must fall an equal proportion to maintain the original system reliability.**

3. **An equal rise in reliability of all items in a series causes a larger rise in system reliability.**
For a 1.9% effort there was a gain of 5.8% from the system. This is a 300% return on investment. Series Reliability Property 3 seemingly gives substantial system reliability growth for free.

These three reliability properties are the key to maintenance management success.

- Series Reliability Property 1 means that anyone who wants high series process reliability must ensure every step in the series is highly reliable.
- Series Reliability Property 2 means that if you want highly reliable series processes you must remove as many steps from the process as possible – simplify, simplify, simplify!
- Series Reliability Property 3 means that system-wide reliability improvements deliver far more pay-off than making individual reliability improvements.

Understanding the concepts of series system reliability provides you with an appreciation of why so many things can go wrong in your business. Everything interconnects with everything else. Should chance go against you, any defect or error made in any process can one day cause a failure that maybe a catastrophe. If you don’t want to run your business by luck it is critical to control the reliability of each step in every process.

Simplify, Simplify, Simplify

There are two examples of using simplified solutions that require fewer components. A Plummer block with a roller bearing needs 14 parts to do what a bearing in a fixed housing does with 5 parts. The Plummer block is a complicated and difficult way to carry a bearing and suffers many bearing failures when in service. It is easy to understand why when there are so many ways for it to go wrong.
There are design engineers across the world that specify Plummer blocks throughout all their 30-40 year long careers. They unknowingly cause the users of their designs lots of problems and many breakdowns because there are so many parts present. With 14 components available to make mistakes on during installation it is almost impossible to get long service life from bearings mounted in Plummer blocks.

Fan drives, such as those for the cooling towers shown in the bottom drawings, can be simplified by the use of variable speed drive electric motors. That choice removes four items from the old style series arrangement and makes the drive far more reliable.

Reliability Properties for Parallel Systems

\[ R_{\text{system}} = 1 - [(1 - R_1) \times (1 - R_2) \times \ldots \times (1 - R_n)] \]

Properties of Parallel Systems
1. The more number of components in parallel the higher the system reliability.
2. The reliability of the parallel arrangement is higher than the reliability of the most reliable component.

Which arrangement is more reliable if \( m = 0.9 \)?
What percentage improvement is the more reliable?

A parallel system has certain properties from which implications of parallel system behaviour and constraints can be drawn. The left-hand arrangement is the more reliable, having a reliability of 0.98 vs 0.964.
The Reliability of **Systems** of Parts and Components (i.e. a Machine)

The shape and position of the ‘system’ curve is adjustable by varying the policies controlling quality and maintenance!

The reliability of a machine is always less than its parts. When one part fails the whole machine fails. With many parts in a machine, there are many chances of failure.

To improve the reliability of a series of parts (that’s a machine) we must improve the reliability of each part. We must ensure each part gets its maximum life.

When components are combined together into a machine or assembly they form systems of parts. The system fails every time a component fails. Hence system reliability is lower than individual component reliability.

The wavy curve is the reliability of a single machine. As its parts fail the machine reliability curve moves. It goes upward, indicating high rates of failure, when many parts break often, and downwards (indicating reduced rates of failure) when parts do not fail. The message to take away is that if you want highly reliable machines you must first have highly reliable parts.

When we have many identical machines run under identical conditions then we get the olive coloured an average curve for the entire group of machines.

To improve system reliability it is necessary to either improve individual component reliability, or to include redundancy. In all cases it is worthwhile to adopt system-wide best practices, as they benefit every part of the system.

Within the slide is shown various strategies to adopt to reduce the chance of failure, depending on the stage of the equipment life cycle.
Since reliability can only be improved if failure is prevented, the diagram asks what can be done at the various stages of equipment life to deduce the chance of failure occurring. By selecting the right strategies and practices we can mould the chance of failure curve to what we want.

“Equipment reliability is malleable by choice of policy and quality of practice.”
The purpose of maintenance is to deliver improving equipment reliability. We do that by continually removing the risks that cause equipment parts to fail. Parts failure curves are malleable; they can be changed by the selection of engineering, operating and maintenance policies and practices.

This story of the diesel engines used on a ship that had three times less maintenance cost than identical engines used in a locomotive is illuminating.

Retired Professor of Maintenance and Reliability, David Sherwin, tells this story in his reliability engineering seminars of the financial consequences for two organisations with different strategic views on equipment reliability. Some years ago a maritime operation brought three diesel engines for a new ship. At about the same time, in another part of the world, a railway brought three of the same model diesel engines for a new haulage locomotive. The respective engines went into service on the ship and the locomotive and no more was thought about either selection. Some years later the opportunity arose to compare the costs of using the engines. The ship owners had three times less maintenance cost than the railway. The size of the discrepancy raised interest. An investigation was conducted to find why there was such a large maintenance cost difference on identical engines in comparable duty. The engines in both services ran for long periods under steady load, with occasional periods of heavier load when the ship ran faster ‘under-steam’ or the locomotive went up rises. In the end the difference came down to one factor. The shipping operation had made a strategic decision to de-rate all engines by 10% of nameplate capacity and never run them above 90% design rating. The railway ran their engines as 100% duty, thinking that they were designed for that duty, and so they should be worked at that duty. That single decision saved the shipping company 200% in maintenance costs. Such is the impact of small differences in stress on equipment parts.

Simply because of the policy decision to de-rate their duty to 90% of nameplate capacity. The evidence of successful reliability improvement shows up as falling rates of parts failure and greater MTBF of equipment. The Figure shows the changed failure rate of equipment parts by choice of appropriate policies and use of the required methods.

Reducing the influence of chance and luck on equipment parts starts by deciding what engineering and maintenance quality standards you will specify and achieve in your operation. For example, what number of contaminating particles will you permit in your lubricant? The lower the quantity of particles, the higher the likelihood you will not have a failure. What balance standard will you set for your rotors? The lower the residual out-of-balance forces, the smaller the possibility that out-of-balance loads will combine with other loads to initiate or propagate failures. How accurately will you specify fastener extension to prevent fasteners loosening or breaking? The more precise the extension meets the needs of the working load, the less likely a fastener will come loose, or fail from overload. These are probabilistic outcomes that you influence by specifying the conditions and standards that produce excellent equipment reliability and performance.

The degree of shaft misalignment tolerated between equipment directly impacts the likelihood of roller bearing failure. The frequency and scale of machine abuse permitted during operation directly affects the likelihood of roller bearing failure. The standard achieved for rotating equipment balancing directly influences the likelihood of roller bearing failure. The temperatures at which bearings operate change their internal clearances, which directly influence the likelihood of roller bearing failure. The same can be said for every other factor that affects
the life of a roller bearing. Similar statements about the dependency of failure on the probability of failure-causing incidents can be said of every equipment part. Chance and luck determine the lifetime reliability of all parts, and consequently all your machines and rotating equipment. But the chance and luck seen by your equipment parts is malleable. For example, you can select lubricant cleanliness limits that greatly reduce the number of contaminant particles. With far fewer particles present in the lubricant film there is marked reduction in the possibility of jamming particles between load zone surfaces. Combine that with ensuring shafts are closely aligned at operating temperature, that rotors are highly balanced, that bearing clearances are correctly set, that operational abuse is banned and replaced with good operating practices to keep loads below design maximums, and you will greatly improve your ‘luck’ with equipment reliability. You can have any equipment reliability you want by turning luck and chance in your favour through your quality system.

In 1939 Waloddi Weibull developed a distribution curve that has come to be used for modelling the reliability (i.e. failure rate) of parts and components. The Weibull distribution uses a part’s failure history to identify its aging parameters. One of these is the beta parameter, which depending on its value indicates infant mortality (<1), random failure (~1) or wear-out (>1 to 4).

Once the primary mechanism of failure is known appropriate practices can be put into place to remove or control the risk of failure. Infant mortality can be reduced by better quality control, or it can be accepted as uncontrollable and all parts overstressed intentionally to make the weak ones fail. The resulting parts will then fail randomly. In the case of random failure there is no certain age at which a part will fail and all that can be done is observe it for the onset of failure and replace it prior to complete collapse. When a part has a recognisable wear-out it is replaced prior to increased rate of failure.

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Implications of Reliability on Maintenance

• If your machines have parts that show age-based failure, then replace the parts on an accumulated usage basis. (Not on a time basis, unless environment degrades the material.)

• But if you have machines with parts that can fail at any time, and they can last a long time, then when do you replace them?

What now becomes important is how ‘stressful’ has each part’s life been to this point in time? How many failure modes has it seen?

That is dependent on what happened to it during its operating service. This means we must know the part’s condition all the time. Especially we must count the number and size of ‘stress’ excursions of all failure modes.

• Rebuilds DO NOT return equipment to ‘as new’, since new parts are mixed with parts that have seen service. Parts with service are ‘stressed’ and have used-up part of their life. Rebuilt equipment containing old parts do not last as long as new equipment.

Knowing that most components fail according to probabilistic events, it becomes necessary to identify what influences the probability, or likelihood, or chance of those events occurring. If the chance of failure can be reduced, then the number of failures will decrease and as a consequence the reliability rises.

We need to appreciate what the ‘life of parts’ means to the maintenance of equipment. If the parts age with use, we replace them after the use accumulates to the allowed amount. If parts are chance-failure based, and are not stressed, they will last indefinitely. But if they are stressed we must check the part’s condition and decide how much life is left in it.

Each rebuild of machinery does not return it to ‘as new’ condition, unless every part is renewed and the item rebuilt to manufacturer’s specification. You would then be better-off, and pay less, to get all-new equipment.

There is a story about a bus company in the United Kingdom that had a policy to always rebuild its bus gearboxes. After many years they had collected a lot of failure data and history on their fleet’s gearbox life. They found that every rebuild on average lasted half the previous rebuild lifetime. By the time a gearbox was rebuilt a fifth time it failed after only a few months.

If you use old parts on a rebuild you put back tired and aged parts along with new parts. The new parts start stronger with a new, unstressed microstructure. The old parts have a used and stressed microstructure that can take lesser stress accumulation before they fail. The old parts fail soon after the rebuild is put back into service.
When and How Much Maintenance?

• If a part ages/wears with use, replace it after use accumulates to the allowed amount. (PM)

• If a part’s life is chance-failure based, and was not stressed, it will last indefinitely. (Precision Maintenance)

• But if it was stressed we must check the part’s condition to decide how much life is left in it, and when to replace it. (PdM)

Using the Bill of Materials do an FMEA to identify how each part will fail AND how the failure mode stresses can be controlled, and preferably prevented.

Do you replace the damaged parts only, or all parts in this system?

How often do you rebuild Haulpack truck gearboxes?

If we know how our parts are going to fail we can monitor for signs of the failure. But more importantly, we can control the operating conditions and environment to ensure stresses are limited to those that will not cause rapid life reduction.

When parts replacement is required we must ask whether to only replace the part needing to be replaced, or the associated parts that it was assembled together with. If the part is being replaced because of failure, then the associated parts would also have seen high stresses and most likely will need to be replaced as well. Otherwise, because of their accumulated stresses, those parts not replaced will fail sooner than the new parts when they are next over-stressed. And the equipment taken out for repair just a while ago is again out for repair.

In Australia, one Caterpillar Haulpack mining truck agency only rebuilds truck gearboxes twice before completely replacing them with a new gearbox. They found that after the second rebuild the gearboxes did not last long enough in service and could not justify doing more overhauls on tired, worn and old gearboxes.
That’s another hour over Joe.

Alright, …today we covered some difficult concepts. There will be no question to think about tonight.

That’s okay with me. So what will we cover tomorrow?

Tomorrow is the right time to bring together all the concepts we have covered so far – risk, reliability, physics of failure, the cost of failure – into the maintenance strategy we use, and that you will be continuing with in a couple of months time.

How are you today Ted?

Good morning Joe. Fine thanks.

It’s time to talk about maintenance. This morning I want to explain how maintenance delivers reliability, risk control, low operating costs and high quality product.

I never realised that we maintainers could actually impact the business so much. All we do is look after the equipment.

In a way you are right. We get involved after the operations people use the equipment. So we don’t make the product ourselves. But what we can do is put the machinery into it’s ideal ‘design envelope’ and make sure it is kept there. When we do that the parts aren’t overstressed, the conditions they live in are ideal, our workmanship is of high quality and we monitor for changing conditions.

That morning …
Breakdown Maintenance (BM):
• Maintenance performed after a machine has failed to return it to an operating state.
• Action in the event of unforeseen failure of an asset affecting operations and/or creating a risk hazard.

Corrective Maintenance (CM):
• Repair/refurbish parts once condition deteriorates unacceptably.

Design-Out (DO):
• Treatments correcting existing deficiencies
• Changes made to a system to repair flaws in its design, coding, or implementation.

Block Maintenance (Shutdown):
• Maintenance that can only be performed when equipment is out-of-service. Part of PM.

Opportunity Maintenance (OM):
• Additional maintenance done when equipment is stopped for other maintenance work or production reason

Predictive Maintenance (PdM):
• An strategy based on measuring the condition of equipment to assess whether it will fail during some future period, and then taking appropriate action to avoid the consequences of failure. The condition of equipment can be monitored using Condition Monitoring, Statistical Process Control techniques, equipment performance, or through the use of the human senses. The terms Condition Based Maintenance, On-Condition Maintenance and Predictive Maintenance can be used interchangeably.

Condition Monitoring (Con Mon)
The use of specialist equipment to measure the condition of equipment. Vibration Analysis, Tribology and Thermography are examples

Precision Maintenance:
• Ensuring equipment, foundations, connections, and local conditions achieve high running accuracy of components

There are 6 main maintenance strategies (numbered 1 to 6) which are normally applied on plant and equipment in order to manage risk. From the 6 a selection is made that will hopefully deliver least maintenance costs and maximum plant availability. The selection of a maintenance strategy should be based on achieving the required equipment risk management results.

It is good practice that the chosen maintenance strategies be reviewed at least two-yearly to confirm they are producing the benefits and results originally intended. If not the reasons need to be identified and addressed.

• Breakdown Maintenance (a most expensive forte of the reactive operation)
• Preventive Maintenance (used for replacing only parts that wear-out & no other)
• Predictive Maintenance (used to detect parts failure early enough to prevent downtime)
• Planned Maintenance (putting a maintenance strategy into place)
• Opportunity Maintenance (what other work to do if equipment is down)
• Corrective Maintenance (replacing/refurbishing parts on-condition)
• Reliability Centered Maintenance (spot maintenance problems in the design)
• Design-out Maintenance (design-in reliability & design-out equipment problems)
• Shutdown (block) Maintenance (replace equipment and parts that suffer ageing)
• Total Productive Maintenance (operator driven equipment reliability)
• Precision Maintenance (Using fine craftsmanship to deliver the most reliability, availability & least costs)

Using the strategies is not sufficient to guarantee risk reduction. The ‘human element’ must also be addressed to ensure the strategies are being applied correctly and effectively.
Opportunity Maintenance Explained

OM is when designated un-failed parts in equipment are replaced whenever the equipment is opened for repair of failed items. For example, the Table list shows that when an impeller fails and is replaced, then the pump bearings and seals are also replaced, and so forth.

This is a good maintenance practice to improve reliability by increasing mean times between failure with only minor increases in costs. Develop tables so that when failed items are replaced the associated components are also replaced. Though the old ‘still good’ parts may last, the production savings gained from longer operation because of the reduced chance of early failures more than covers the added cost of all new parts.

Opportunity Maintenance is the practice of replacing un-failed parts at the same time as failed parts because the equipment is already open and available. With a little more expense for the extra new parts, and a bit more labour, you put back into service equipment that should now run for longer before any of the replaced parts fail.
Match Maintenance Strategies to Risk

Doing Maintenance must produce Risk Reduction.

*Move from Reactive to Proactive to Risk Reduction.*

Operating Risk = Consequence of Failure x (Frequency of Opportunity x Chance of Failure)

The maintenance strategies we use need to be matched to operating risk so that by doing them the risk falls.

Where risk is high, proactive strategies to remove problems reduce the likelihood of failure and so lower the maintenance costs from breakdowns. Where risk is low, consequence reduction strategies that happen after failure starts can be applied because the cost of failure is low. Chance reduction strategies are viable in all situations, but consequence reduction strategies must be carefully chosen because they do not prevent failure, rather they only minimize the extent of the losses. Hence using condition monitoring in high risk conditions must be accompanied with rapid response capability to address the failure before it goes to a breakdown.
Many current maintenance strategies involve significant wasted effort; scheduled intrusive actions on “healthy” equipment, and condition based activities based upon “How might my machine fail?”

There is a requirement to consider risk/criticality of the specific item of equipment when selecting maintenance activities. The expenditure of maintenance dollars on risk management (eg condition monitoring, process control, etc) should be directly related to the probability and consequences of that equipment’s failure. This is a very significant decision point in the management of condition monitoring expenditure!

We need a process that lets us identify the size of an operating risk carried by an item of equipment, especially the frequency of a potential failure event, and which then lets us select the best maintenance and operating strategies to minimise that risk. By targeting the risks to an equipment item we reduce wasted maintenance effort that produces no risk mitigation. We can even go further and use maintenance to remove risk altogether.

Often reasonable judgements based on experience can be made without the rigour and expense of exhaustive failure modes analysis. Sometimes, however, a formal risk assessment must be done and decisions undertaken based on those outcomes.
What Maintenance Causes Reliability

To reduce operating risk we make defensive provisions to ensure the chance and/or consequence associated with a scenario was adequately low.

(Risk professionals say to set Asset Impact on worst likely event – i.e. pessimistic but not Maximum Credible worst Consequences, but I start with worst possible since we need to do those activities that make sure they won’t happen.)

E.g. It is possible that the only High Voltage (HV) power supply transformer (TX) to a site could fail. So regular PM and CM testing are specified to keep the likelihood, and thus the risk, low.

However, the Item retains the Impact associated with the consequences of this failure. The credible but highly unlikely possibility that the TX could also catch fire is usually excluded on the basis that safety systems W/Os (PMs and CMs) are always completed on schedule.

By doing the WOs we gain more information about the TX current condition and its risk. But failure to complete a PM or CM task will move us from the design criticality towards the unmitigated risk due to our lack of knowledge of TX condition.

Thus in terms of Operating Risk: a PM or CM on a HV T/X may be higher priority than a repair to a failed lower Impact Item

The risk control strategies chosen are critical to minimising operating costs and creating equipment reliability. Doing maintenance that does not reduce risk is pointless.

Operating plants who want to reduce costs need to identify the causes of their costs and remove them. Adding maintenance routines to control risks will immediately cause maintenance costs to rise. The added maintenance is beneficial if it reduces DAFT Costs by stopping risks becoming failures. It will be some months before new maintenance reduces failure frequency so that savings show-up in monthly reports. Doing the right maintenance reduces risks becoming failures, but it will not remove the opportunity for failure. For the least operating and maintenance costs it is necessary to remove the chance of failure.

Protecting the only power transformer supplying an operation is vital. If a replacement transformer DAFT cost is $2M and it takes 26 weeks to make a replacement TX, it is clear that the TX already installed cannot be allowed to fail. To reduce operating risk we put selected maintenance activities into place that protect the transformer. But it is only when doing the maintenance properly and on-time that the TX is actually protected. This means that those work orders that protect critical assets from failure must be done when they fall due, else the risk of failure starts to rise.

Notice that the maintenance that produces reliability is that work which causes the frequency of failure to fall. When fewer failures occur in a given time period the reliability has been improved. Condition monitoring does not improve reliability because CM only finds failures once they have started.

The maintenance work that creates reliability is that work that prevents failure causes arising—the work undertaken stops problems happening. Because there are no causes to start a failure there is no downtime, and so reliability rises.
Risk Influenced Maintenance Strategy

If the answer is NO then either Planned Preventive or Breakdown Maintenance will be applied, depending upon the Criticality or Risk.
If the answer is YES and the Criticality justifies it then Condition Based Maintenance will be applied.
If the answer is YES but Criticality does not justify it then Planned Preventive or Breakdown Maintenance will be applied.

However, this does not result in least maintenance cost... because failure is allowed to happen.

We are required to identify the possible ways in which equipment may fail, and consider if it is possible to detect and measure the failure process.

Back in the 1970’s the aircraft industry used an aircraft’s previous failure history for “hindsight” in decision-making through the use of the Reliability Centred Maintenance methodology. The approach required that every item of plant (system, machine, component) be reviewed, criticality (risk) considered, and a decision made on the maintenance it will get – repair by Replacement, Scheduled, or Condition Based.

This concept was readily accepted by the airline industry where risk meant death of passengers. So in aircraft, safety drove the selection of maintenance strategy to protect people against failures. However failure is a result of parts being unable to meet their duty. When RCM was used by general industry it focused people on managing risk like it was done in the airline industry by using maintenance strategy to detect onset of failure. That approach totally missed the fact that parts do not fail if there is no cause of failure. By focusing on controlling the consequences of risk, and not on eliminating of the causes of failure, RCM ingrained maintenance as the primary strategy for risk control in industry. The ideal risk control strategy is to remove the risk, not leave the risk in place and look to see if there is a problem caused by the risk that now needs to be fixed.

Precision Maintenance (PrM) is the correct and best strategy to use to prevent equipment risk. PrM removes and prevents the stresses that cause failures. There is no value in condition monitoring if a machine is set-up with precision, operated with precision and its parts maintained in precision environments. In such a situation there is nothing more humanly possible to do to make the machine live a long, trouble-free life. Condition monitoring would not find a problem and would therefore be a waste of time and money.
7. Activity 3 – Prove Maintenance Tasks bring Reliability

**Activity 3 – Are the maintenance tasks truly effective in preventing failure? What activities need to be done to make the valve reliable?**

The expanded section of spreadsheet copied from the lower table shows the results of a RCM analysis on an automated suction control valve at a compressed natural gas pipeline compressor station. The team selected the five activities listed to care for the valve and maximize its uptime. The top three require performing a valve integrity test where the valve is removed, stroked and repaired as necessary. The last two are external inspections of the valve while in operation.

The additional work may be a total waste of time unless it actually makes the valve more reliable by doing those activities. If each of the activities is useful in preventing failure their effect should be observable in a risk matrix as a lowering of the risk compared to them not being done. If the risk reduces on the matrix then you are sure that the activity will lower the risk and hence prevent losses and downtime.

Should a valve fail the DAFT Costs are $200,000. On average a valve will fail every 5 years. The additional work created by the RCM will need to decrease the failures to fewer than one per five years. If the new work does not improve reliability then it is a waste of time and should not be done. Instead find useful work to do that does make the valve more reliable.
### Review Effectiveness of RCM Recommendations

<table>
<thead>
<tr>
<th>Location</th>
<th>System, Maintenable Item/Assembly performing function</th>
<th>Failure Mode (What happens)</th>
<th>Failure Cause (Due to)</th>
<th>Failure Effect on operations</th>
<th>Likelihood rating</th>
<th>Criticality rating</th>
<th>Mainten Strt (Detectability, FTT, PM/ConMon, FT, OTF)</th>
<th>New Maintenance Task Description</th>
<th>Online / Offline</th>
<th>New Frequency &amp; Units</th>
<th>Acceptable limit</th>
<th>Secondary task</th>
<th>Disciplines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Valve Assembly - Unit 2 Suction Valve</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**System, Maintainable Item/Assembly performing function**
- Valve Assembly - Unit 2 Suction Valve

**Failure Mode (What happens)**
- seat damage: age
- seat damage: contamination
- seat damage: operation under high dP
- External valve body seal leaks: age

**Failure Cause (Due to)**
- inefficiency of isolation
- inefficiency of isolation
- inefficiency of isolation
- inefficiency of isolation

**Criticality rating**
- 4
- 5
- 20
- 4
- 5
- 20
- 3
- 5
- 15
- 3
- 5
- 15

**Mainten Strt (Detectability, FTT, PM/ConMon, FT, OTF)**
- PM
- PM
- PM
- PM

**New Maintenance Task Description**
- Perform valve integrity test
- Perform valve integrity test
- Perform valve integrity test
- Check condition of valve

**Online / Offline**
- Offline
- Offline
- Offline
- Online

**New Frequency & Units**
- 12 Monthly
- 12 Monthly
- 12 Monthly
- Each zonal

**Acceptable limit**
- No leaks
- No leaks
- No leaks
- No corrosion

**Secondary task**
- Replace value
- Replace value
- Replace value
- Remove and inhibit corrosion

**Disciplines**
- Mech
- Mech
- Suction & Discharge
- PMO
- Suction & Discharge

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**Website:** www.lifetime-reliability.com
Measure IF Likely Improvement from Work

We can plot the current location of risk from the $200 DAFT Cost and the 5-year frequency of failure. The question is whether the new maintenance work will reduce the risk by significantly more than it costs to do the work.

A valve integrity test means removing the valve from the pipeline and placing it on a test bench where the valve internals can be checked for problems and wear and operated under controlled test conditions. Once the valve is in the test position it is stroked and its stem movement and seating/sealing behavior checked for compliance to an acceptable standard.

An integrity test proves the valve works properly or not. A valve will either pass or fail the test. Performing the test does not make the valve more reliable, it only spots a problem after it has happened. When a problem is found it is fixed or parts are renewed. The valve is then put back into the same service situation as it was found to undergo the same conditions that caused its current reliability and performance.

The visual inspections look at the valve condition. The valve will either be fine or it will not. Again the inspection does not make the valve reliable, it only spots a problem after it has happened.

The $20,000 spent on every valve every year will not stop a single valve from failing. The best that can happen is old parts that no longer behave properly are replaced with pristine and they will start life from new. Parts not replaced will age further and fail.

A better strategy is to replace all valves every 5 years with fully refurbished units properly rebuilt and do no other maintenance. The best strategy would be to fix the problems that make the valves fail—stop contamination, moisture, and over-pressure operation.
### RCM Activity Risk Criteria

#### Likelihood Criteria

<table>
<thead>
<tr>
<th></th>
<th>Hypothetical</th>
<th>More than 100 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Remote</td>
<td>One per 20-100 years</td>
</tr>
<tr>
<td>3</td>
<td>Unlikely</td>
<td>One per 10-20 years</td>
</tr>
<tr>
<td>4</td>
<td>Rare</td>
<td>One per 3-10 years</td>
</tr>
<tr>
<td>5</td>
<td>Occasional</td>
<td>One per 1-3 years</td>
</tr>
<tr>
<td>6</td>
<td>Often</td>
<td>1-5 per year</td>
</tr>
<tr>
<td>7</td>
<td>Frequent</td>
<td>5-10 per year</td>
</tr>
<tr>
<td>8</td>
<td>Very frequent</td>
<td>&gt;10 per year</td>
</tr>
</tbody>
</table>

#### Consequence Criteria

<table>
<thead>
<tr>
<th></th>
<th>Supply/Outrage</th>
<th>People</th>
<th>Environment</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Trivial</td>
<td>No process consequence</td>
<td>No injuries</td>
<td>No effect</td>
</tr>
<tr>
<td>2</td>
<td>Minor</td>
<td>Disruption to effective local asset/system operation (immediately rectified)</td>
<td>Injuries not requiring First Aid treatment</td>
<td>Negligible on-site effects rectified rapidly with negligible residual effect</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>Disruption to effective local asset/system operation (&lt;1 day)</td>
<td>Injuries not requiring First Aid treatment</td>
<td>Negligible on-site effects rectified rapidly with negligible residual effect</td>
</tr>
<tr>
<td>4</td>
<td>Moderate</td>
<td>Disruption to effective local asset/system operation (&lt;1 day)</td>
<td>Injuries not requiring First Aid treatment</td>
<td>Minor on-site effects rectified rapidly with negligible residual effect</td>
</tr>
<tr>
<td>5</td>
<td>Severe</td>
<td>Disruption to pipeline capacity or shipper supply (capacity reduced by &lt;30% for &lt;1 day)</td>
<td>Injuries requiring first aid treatment</td>
<td>Effect very localised (&lt;0.1 ha) and short term (weeks); easy rectification</td>
</tr>
<tr>
<td>6</td>
<td>Major</td>
<td>Disruption to pipeline capacity or shipper supply (capacity reduced by &lt;30% for 1-2 days)</td>
<td>LTIs or MTIs</td>
<td>Effect very localised (&lt;0.1 ha) and short term (months); easy rectification</td>
</tr>
<tr>
<td>7</td>
<td>Critical</td>
<td>Disruption to pipeline capacity or shipper supply (capacity reduced by &gt;30% or 2 days to 1 week)</td>
<td>Permanent injuries</td>
<td>Localised (&lt;1 ha) and short term (&lt;2 yr) effects; significant impact on cultural and heritage sites or rare and endangered fauna/fauna</td>
</tr>
<tr>
<td>8</td>
<td>Catastrophic</td>
<td>Total supply interruption, or major disruption to pipeline capacity (&gt;30% capacity for up to 2 weeks)</td>
<td>Fatality</td>
<td>Major offsite impact; long term (&gt;2 years) sever effects; rectification difficult</td>
</tr>
</tbody>
</table>

#### Risk Matrix

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Trivial</td>
<td>Minor</td>
<td>Low</td>
<td>Moderate</td>
<td>Severe</td>
<td>Major</td>
<td>Critical</td>
<td>Catastrophic</td>
</tr>
<tr>
<td>2</td>
<td>Very Frequent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Frequent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Often</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Occasional</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Rare</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Unlikely</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Remote</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Hypothetical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Risk Assessment Matrix (to prove financial benefit)

## Calibrated Risk Matrix

Calibrate the matrix to reflect your Operations business-wide impact of failure

The cost consequence is estimated on the DMT Costing worksheet.

The likelihood is determined from the historic frequency occurring in your operations or from other comparable operations.

## Likelihood of Equipment Failure Event per Year

<table>
<thead>
<tr>
<th>Event Count per Year</th>
<th>Time Scale</th>
<th>Descriptor Scale</th>
<th>Historic Description</th>
<th>Cost of Failure per Event</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1k</td>
</tr>
<tr>
<td>160</td>
<td>Twice per week</td>
<td>2</td>
<td></td>
<td>3.5</td>
</tr>
<tr>
<td>30</td>
<td>Once per fortnight</td>
<td>1.5</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>Once per month</td>
<td>Certain</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Once per quarter</td>
<td>0.8</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>1</td>
<td>Once per year</td>
<td>Almost Certain</td>
<td>Event will occur on an annual basis</td>
<td>0</td>
</tr>
<tr>
<td>0.2</td>
<td>Once every 2 years</td>
<td>Likely</td>
<td>Event has occurred a few times in a lifetime career</td>
<td>-0.5</td>
</tr>
<tr>
<td>0.1</td>
<td>Once per 10 years</td>
<td>Possible</td>
<td>Event might occur once in a lifetime career</td>
<td>-1</td>
</tr>
<tr>
<td>0.03</td>
<td>Once per 30 years</td>
<td>Unlikely</td>
<td>Event does occur somewhere from time to time</td>
<td>-1.5</td>
</tr>
<tr>
<td>0.01</td>
<td>Once per 100 years</td>
<td>Rare</td>
<td>Heard of something like it occurring somewhere</td>
<td>-2</td>
</tr>
<tr>
<td>0.003</td>
<td>Once every 300 years</td>
<td>Almost Certain</td>
<td>Theoretically possible but not expected to occur</td>
<td>-3</td>
</tr>
<tr>
<td>0.001</td>
<td>Once every 1,000 years</td>
<td>Very Rare</td>
<td>Never heard of this happening</td>
<td>-5</td>
</tr>
<tr>
<td>0.0003</td>
<td>Once every 30,000 years</td>
<td>Almost Incredibly</td>
<td>Theoretically possible but not expected to occur</td>
<td>-6</td>
</tr>
<tr>
<td>0.0001</td>
<td>Once every 100,000 years</td>
<td>Almost Incredibly</td>
<td>Theoretically possible but not expected to occur</td>
<td>-7</td>
</tr>
</tbody>
</table>

### Notes

1. **Risk Level**:
   - Red = Extreme
   - Amber = High
   - Yellow = Medium
   - Green = Low
2. **Risk Management**:
   - 1) Risk boundary: Low level is set at $10,000 11/11/11
   - 2) Based on pre populous
   - 3) Identify Black Swan event or $5 ($A Black Swan event is one that people say will never happen because it has not yet happened)
   - 4) DMT Cost (Defect and Failure True Cost) is the total business-wide cost from the event
Failure Cause Elimination Brings the Greatest Benefits

<table>
<thead>
<tr>
<th>Tactic</th>
<th>Up time</th>
<th>% Change</th>
<th>% Uptime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactive</td>
<td></td>
<td></td>
<td>83.5%</td>
</tr>
<tr>
<td>Planning Only</td>
<td>+ 0.5 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scheduling Only</td>
<td>+ 0.8 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preventive / Predictive Only</td>
<td>- 2.4 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All three tactics</td>
<td>+ 5.1 %</td>
<td></td>
<td>88.6 %</td>
</tr>
<tr>
<td>Plus Failure Elimination</td>
<td>+ 14.8 %</td>
<td></td>
<td>98.3%</td>
</tr>
</tbody>
</table>

DuPont found that planning and scheduling don’t, in themselves, actually make a big difference in lifting reliability and plant availability. What makes the difference is eliminating the causes of failure. This is where the Maintenance Planner must focus their efforts – they must use their planning time and systems to ensure that defects and failures are prevented and eradicated.

This table shows DuPont’s experience in improving their production processes. They tested various means to get higher uptime in a reactive organisation. Done individually, planning and scheduling produced little improvement. The introduction of inspection based maintenance alone actually lowered plant availability. This was likely due to the need to bring plant down for inspection, which disrupted production and caused lost time. When done in combination, the three strategies delivered clear improvement.

But the greatest improvement in uptime was achieved when efforts were made to remove the causes of failure that prevented the plant running at full availability. The DuPont experience reinforces the value and sense of stopping defects and failures from happening in a business.
This table shows the production time loss represented by various Availability values for a continuous operation. World class continuous process operations are at or above 98%.

Once you know the production required, you divide the equipment rated capacity per time period, into the production target and come-up with the period the plant has to run at full capacity to meet the plan. If the plant must be run above capacity to meet the target, you automatically know that the equipment parts will be overstressed and the risk of failure will rise. You also can identify what risks will prevent the production plan from being achieved and then put in place suitable risk mitigations.

One other take-away from the table is that availability increase is a major improvement project. To go from 80% to 90% availability you must halve your downtime. To go from 90% to 98% you must remove 30 days of time loss. To do that in any company is a huge project that requires dedicated people, capital and resources.

You cannot just ask for higher availability and it will happen—changing availability greatly is very hard work and needs people and money committed to its accomplishment.

**Calculating Availability / Uptime**

First define what Availability or Uptime mean in your operation. Second, specify the reporting period – daily, weekly, monthly, etc. Thirdly, determine how it will be presented to people; what will it look like.

What time will you include as lost production? How will you measure the various time losses? Will you report and/or trend the time losses as well?
Who will compile the time loses and who will calculate Availability? Who will ensure it is displayed as feedback?

**Continuous Operating Plant – Work 24/7**

The most severe measure is to calculate Availability after including all time losses.

\[
\text{Scheduled Production Time – Total Lost Time} \\
\text{Scheduled Production Time}
\]

A variation is:

\[
\text{MTBF} = \frac{1}{\text{MTBF + MTTR}}
\]

MTBF = mean time between failure  
MTTR = mean time to repair

**Batch Plant – Work Shift**

The same formula can be used in batch plants, except the scheduled time is for the period of the shift.

\[
\text{Scheduled Production Time – Total Lost Time} \\
\text{Scheduled Production Time}
\]

---

**Set Standards and Standardise their Use**

- Lubrication  
- Vibration  
- Shaft Alignment  
- Balancing  
- Component Stress and Fatigue  
- Component Tolerance  
- Material Selection  
- Equipment Deformation Limits  
- Torque and Tension  
- Looseness  
- Contamination  
- …? …

The more perfect these are achieved, the longer the equipment operates correctly, … which results in greater reliability
Standards are used to provide clear direction and instruction in how to do a task so that the required outcome results. They tend to remove uncertainty and variation from performance. If done correctly, to the standard, the result will be suitable for the needs of the situation.

Standards serve a second purpose of setting the benchmark of acceptance. Anything less than the standard is unacceptable. Until the standard is reached development and training continues.

The third purpose of a standard is to provide a baseline against which audits can be compared.

Reliability improvement standards are aimed at achieving near-perfection results. With standards set for such issues as those listed on the slide, the aim becomes to always be better. In doing so equipment operates in a near-perfect environment within near-perfect tolerances. This gives plant and equipment maximum chance of operating correctly without failure.

A fourth benefit of working to standards is they can be tightened to set a new level of performance. In this way you can instigate continuous improvement.

You must set the standards for the issues listed in the slide and then ensure they are known organisation-wide and are applied and practiced by the workforce.

**Mechanical Equipment Care Standards to Set, Use and Keep Using**

These are the BIG ONES that maintenance can control.

- **Vibration:**

- **Deformation:**

- **Alignment:**

- **Fastener Torque:**

- **Lubricant Cleanliness:**

- **Balancing:**

- **Fits and Tolerance:**

When it comes to mechanical equipment the critical standards listed in the slide must be set and kept. It is necessary to spend the effort in researching and specifying them for your operation. Once they are determined, communicate them to the engineering and maintenance staff company-wide.

Start using them in all situations, and for all subcontractors. If necessary buy, or subcontract with providers, whatever equipment is required to meet them and train your people in how to achieve the standards in everything they do.
If you want top class reliability from mechanical equipment you have no choice but to get very, very good at continually meeting those standards.

Scripting the future of an operation begins by setting the required engineering quality, production quality and maintenance quality standards you will meet. Quite literally, decide what standards that people, plant and processes need to achieve and write them down so everyone knows what they are. They become the level of quality that everyone works to. To go below those quality standards will result in additional and increased risk to the operation from equipment failure, from wasted production processing and from poor work task performance. By scripting the quality standards for an operation, you increase the reliability of every business process. You apply Series Reliability Property 3 to a business - the series reliability property that delivers the greatest benefits – because once a standard is set it drives improvements right across an operation. Without touching a piece of plant, the setting of a higher quality standard decrees the future reliability and performance of all equipment and processes in an operation. Anything that is not up to that standard is changed and improved to meet it.

**Activity 4 – Setting Reliability Standards**

Identify what reliability standards to use for the various types of equipment and situations listed in the table.

The exercise aims to get people to recognise the need to set standards and meet them in order to have reliable equipment.

In the end, a library of procedures and standards for every job and activity in every department is needed – from boardroom to shopfloor. Everyone works to procedures and standards. Nothing is left to chance – even the dress standard. If variation is acceptable in a job, the procedure will tell the amount of variation permitted. Where accuracy and precision are required, the procedure documents it. How will people know what great performance and a world-class result looks like unless it is described for them exactly as it needs to be? Once there is a script of what is a great result, people put plans and actions into place to get there. Without knowing what top class performance looks like, anything will do.
You need to document and explain exactly how all your business processes will be run to get the business outputs. They must be scripted precisely as things needs to happen. Find the right people to compose these documents and give them the time to sit down, research and write the standards, procedures and checksheets you need. Once the documents are drafted, test them in the workplace and correct them from the experience. Re-write them and re-test them until they produce the correct results. Once the standards are set and the procedures are proven they provide the training strategy for the business. Anyone that cannot meet the quality and standards undergoes training to achieve the level of mastery they need to do their work excellently. With certain repeatability in meeting standards you know your business processes are in-control and capable.

8. Activity 4 – Setting Reliability Standards

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Situation</th>
<th>Key Standards to be Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roller Bearing</td>
<td>Gearbox</td>
<td>Oil Cleanliness, Dimensional Tolerance, Shaft Alignment, Frame Distortion, Base-plate Flatness, Oil Contamination, Oil Chemistry</td>
</tr>
<tr>
<td>Centrifugal Fan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plain Bearing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centrifugal Pump</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam Turbine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hazardous Area Instrument</td>
<td>Flammable Goods Storage</td>
<td></td>
</tr>
<tr>
<td>Process Logic Computer (PLC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conveyor Belt Roller</td>
<td>20 km long overland conveyor</td>
<td></td>
</tr>
</tbody>
</table>
Ted, do you see how maintenance contributes to business performance?

That’s it in a nut-shell. We apply the knowledge we know about parts, and systems of parts, to get maximum uptime on each piece of equipment.

I’ll tell you Ted, but please realise that it took me 30 years to arrive at this understanding. What I say may not mean a lot to you, until you see ‘it’ for yourself on your day of ‘enlightenment’. It comes down to doing ‘perfect’ work. When design, purchasing, assembly, installation, operation and maintenance do their work (notice how they form a series process) exactly to the standards that deliver highest reliability – then we will get highest reliability.

Okay, …I’ll take your word for it. But for we maintainers, what do we need to do?

At the end of the session …

Perfect’ work means that we have decided the outcome required of the work and set the necessary standards that represents; then we actually achieve it!
That’s easy Ted … we need to do precision maintenance?

Let’s cover it at our next meeting. I’ve got to get the uptime charts out in-time for this afternoon’s Exec Board Meeting.

How is your day going Ted?

Good thanks Joe. I finally got that report done that I’d been putting off.

Joe, we parted company last time with my question on precision maintenance unanswered.

I’ll explain it now; take a look at this list.

They meet in the morning …
Precision Maintenance of Machinery is …

1. Accurate Fits and Tolerance at Operating Temperature
2. Impeccably Clean, Contaminant-Free Lubricant Life-long
3. Distortion-Free Equipment for its Entire Lifetime
4. Shafts, Couplings and Bearings Running True to Centre
5. Forces and Loads into Rigid Mounts and Supports
6. Laser Accurate Alignment of Shafts at Operating Temperature
7. High Quality Balancing of Rotating Parts
8. Low Total Machine Vibration
9. Correct Torques and Tensions in all Components
10. Correct Tools in the Condition to do the Task Precisely
11. Only In-specification Parts
12. Failure Cause Removal during Maintenance
13. Proof Test for Precision Work and Equipment
14. A quality system to make all the above happen

Number 14 is the one that the vast majority of companies miss. They don’t systemize and standardize the delivery of precision to their machinery.

Precision Maintenance is a set of activities performed by the maintenance crew and operators that produce highly reliable machinery. It requires the achievement of very high standards and tolerances, combined with critical observation and assessment skills to identify and remove potential failures.

The ‘Fourteen Rules’ of Precision Maintenance listed on the slide produce equipment that is exactly as the OEM designed them to operate. This gives the item the maximum chance of running reliably for long periods of time.

Precision Maintenance is the strict adherence to exacting machinery health standards for the entire equipment life cycle. It improves machines and equipment to quality standards where no problems occur during operation. Precision maintenance maintains plant and equipment to the specifications that eliminate the defects and parts failures that cause breakdowns. As a consequence it saves large amounts of money for the companies that use it because:

- their machines and equipment are built not to fail
- there is reduced need for maintenance because parts don’t wear as quickly
- they maximise quality production and stop scrap because machines work properly
- they have vastly fewer stoppages and slowdowns since there are few failures
- fewer spares are used since machines don’t need them
- plant availability and productivity is maximised because machines are reliable

Outstandingly reliable equipment, with exceptional uptime, that delivers unfailingly high production of top quality product, is no accident. Realizing remarkable machinery reliability through Precision Maintenance has been practiced by progressive, proactive organisations since the mid-1980s; achieving both outstanding production performance and the best maintenance cost reductions of all maintenance strategies. Once Maintenance, Operations and Production Managers learn of precision maintenance they acknowledge that it is a great concept and totally
valid; but few implement it. You gain the benefits of precision from your equipment when the business processes used to design it, select it, install it, operate it and look after it create it in your operation.

**Precision Maintenance Delivers Big Savings**

This graph goes back to around 1990 when Update International’s founder, Ralph Buscarello, saw the great worth of precision maintenance in the companies he consulted too. His data indicated that precision maintenance led to the lowest maintenance costs of all strategies. The reason for that is that it removes stress from the parts because they are set-up to run near-perfectly and so had fewer causes of failure.

You may have heard of ‘proactive maintenance’, where efforts are focused at removing the cause of failure. This is not the same as ‘precision maintenance’, which is about meeting high-quality workmanship standards that prevent defect introduction. Precision maintenance is a defect elimination strategy.

There is no mystery why Precision Maintenance lets you make more, ship more, sell more and profit more, while doing it all at less cost – it improves the operating conditions of parts within machinery and reduces their stress levels. Quite literally, your people make your machines run better. Using precision definitely pays well. It is how maintenance contributes to operating profit – by making machines run precisely so failures don’t happen. The money that would have been spent on repairs is retained as greatly improved operating profit.
In this slide Wayne Bissett from OneSteel in Australia shows on a pie-chart that within three months half of the equipment that was repaired at OneSteel would again be repaired. This is evidence of high incidence of Early Life Failure. He makes the point in the graph that we must hit the ‘sweet spot’ on all machinery critical parameters to make any real difference to the life of machines. He has developed a chant that makes clear what we need to deliver to our machines – “Only precise, smooth, tight, dry, clean and cool will do.”

To live in the ‘sweet spot’ requires determining and setting standards for every piece of plant and equipment in an operation, down to the nuts and bolts, for all electrical connections, motor base plates, gearboxs – every component – that addresses issues such as:

- Distortion
- Looseness
- Lubrication
- Cleanliness
- Shaft alignment
- Balancing
- Temperature
- Vibration
- Assembly accuracy
- Installation accuracy
- Tools and condition for use
- Skills and their competency
- Job Records
- Calibration of equipment
- Everything else the equipment parts require for a lifetime of low stress, health and wellness
The standards are measurable, they define the ‘engineering numbers' that are proof of compliance to the standard. Standards need to be researched and agreed to address such issues as:

- the correct tension in every fastener
- the number of threads protruding from a tightened nut
- the maximum size and amounts of contamination you will accept in your lubricant
- the exact gap between parts that you can test with feeler gauges
- the size and dimensional tolerance for a shaft at a bearing location
- the amount of damage you will accept in a part before you replace it with new
- the exact distance along a shaft from a datum to mount a shaft seal
- the exact alignment accuracy between drive shafts

Every part on every machine and piece of equipment in an operation will need standards that guarantee their health. Once you have standards that you can measure, you can prove if a thing is right or not. With measurements to prove the minimum standards are met, you know, almost without question, you are within requirements. You are virtually certain that the job is right and the equipment will run precisely and operate under precision conditions. What uncertainty remains would be due to the risk of using out-of-calibration test equipment that gave a false reading. But the quality management system controlling the condition of your maintenance tools should have prevented that.

Precision Brings Reliability to Equipment

When you start a precision maintenance program, your intention is to introduce precision requirements into the everyday workplace practices. Everything that relates to the plant and
equipment will need to meet those standards. That includes controlling the quality of the original equipment manufacturers, project and design selection, procurement and storage, plant and equipment installation, operations and maintenance, and all subcontract work sent out. It requires confirming the quality of the work performed was to the standards. You need records of how well equipment was built, what was used to build it, the exact conditions it was built under and how it was operated and maintained over its entire life. Nothing during the life cycle that affects the health and wellness of the equipment is left to chance. If you do leave things to chance to decide, it is certain that many times it will go badly, because not everyone one knows what is right, and those that do not know the right answer, and have no way to find it, will guess. If that happens, chance and luck take over the decision making in your company.

Introducing Precision Maintenance requires training in best-practice precision skills, supported in the workplace by a top-class engineering ‘body of knowledge’ including machinery and maintenance standards. If you want equipment in your operation at consistently high reliability, the maintenance and operations people need to develop higher work skills and quality practices that they do not yet have. To develop those skills requires setting high levels of excellence and then training people to them. Many managers, operators and tradespeople will not believe they need such high skills in their operation. This of course is a fundamental error in their thinking. They do not realise that their current processes are not capable of delivering the reliability they want, and explains why many businesses that are busy with improvement efforts still suffer poor availability and breakdowns; they are improving practices that have naturally wide ranges of outcome. Providing tradespeople with a tension wrench to tighten fasteners has little effect on the number of loose and snapped fasteners. If you require tension in fasteners to be accurate to ±10% and provide your people with a process that delivers ±25% variation, there is no chance of consistent success.

**Typical Standards for a Precision Maintenance Program**

1. **Accurate Fits and Tolerance** – ISO/ANSI Shaft/Hole Tolerance Tables
2. **Clean, Contaminant-Free Lubricant** – ISO 4406, ISO 11500
3. **Distortion-Free Equipment** – Shaft Alignment Handbook – Piotrowski
4. **Rotating Parts Running True** – Shaft Alignment Handbook
5. **Forces and Loads into Supports** – Shaft Alignment Handbook
6. **Accurate Alignment of Shafts** – Shaft Alignment Handbook
7. **High Quality Balancing of Rotating Parts** – ISO 1940
8. **Machine Vibration** – ISO 10816
10. **Correct Tools in Condition** – ‘As-New specification’
11. **Only In-specification Parts** – OEM specifications, Machinery Handbook
12. **Failure Cause Removal During Maintenance** – Creative Disassembly; ‘5 Why’
13. **Proof Test for Precision Work and Equipment** – Measurement, Condition Monitoring on Start-up
14. **A system to use the standards successfully** – ACE 3T Procedures

The last item in the list of key Precision Maintenance requirements is the glue that keeps the rest together. It requires installing a business process that ensures the other requirements are
delivered to every machine and equipment item in the operation. The solution is to use the Accuracy Controlled Enterprise procedural tools to turn precision into standardised procedures. With ACE in place you have the tool to drive amazing equipment reliability and production results. You solve equipment performance problems forever. And, more importantly, it lets you make Precision Maintenance a habit throughout your operation. In a nutshell introducing a Precision Maintenance Program consists of:

1. Corporate approval to implement precision maintenance and precision practices
2. Agreement across the operation on the plant and equipment to be precision maintained
3. Agreement across the operation on the precision standards to use for the plant and equipment
4. Agreement across the operation on the best practices to be applied to meet the standards
5. Agreement across the operation on the measurement methods that will prove compliance to standards
6. Writing ACE 3T procedures for all maintenance and inspection activities on the selected plant and equipment
7. Conducting a gap analysis to identify necessary test equipment, specialist tools and facilities
8. Identify any needed skills to be learnt by on-the-job training and expert support
9. Applying the ACE 3T procedures and refining their use
10. Monitoring the effect of the program on plant performance
11. Continually improving the use of precision skills and practices
12. Expanding the program to other plant, equipment and sites

Outstandingly Reliable Machines Require...

<table>
<thead>
<tr>
<th>REQUIREMENT</th>
<th>TARGET</th>
<th>TOLERANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Chemically correct, Contaminant-Free Lubricant</td>
<td>Right Viscosity: &lt;100ppm water; ISO12/9</td>
<td>&lt;14/11</td>
</tr>
<tr>
<td>2. Accurate Fits and Tolerance at Operating Temperature</td>
<td>Form IT5, Temperature to design</td>
<td>&lt;IT7</td>
</tr>
<tr>
<td>3. Shafts, Bearings and Couplings Running True to Centre</td>
<td>IT5</td>
<td>&lt;IT7</td>
</tr>
<tr>
<td>4. Distortion-Free Equipment for its Entire Lifetime</td>
<td>IT5</td>
<td>&lt;IT7</td>
</tr>
<tr>
<td>5. Forces and Loads into Rigid Mounts and Supports</td>
<td>No Looseness; Safely absorb/dampen forces</td>
<td></td>
</tr>
<tr>
<td>6. Accurate Alignment of Shafts at Operating Temperature</td>
<td>Coupling/Feet offset 10µm/20µm</td>
<td>&lt;20µm/40µm</td>
</tr>
<tr>
<td>7. High Quality Balanced Rotating Parts</td>
<td>G1</td>
<td>&lt;G2.5</td>
</tr>
<tr>
<td>8. Total Machine Vibration Low</td>
<td>1.5mm/s rms</td>
<td>&lt;3mm/s</td>
</tr>
<tr>
<td>9. Correct Torques and Tensions in all Components</td>
<td>±5% of correct tension</td>
<td>±10%</td>
</tr>
<tr>
<td>10. Correct Tools in Precise Condition to do Task to Standard</td>
<td>As new condition/calibrated</td>
<td></td>
</tr>
<tr>
<td>11. Only In-specification Parts</td>
<td>OEM approved material and design specs</td>
<td></td>
</tr>
<tr>
<td>12. Failure Cause Removal during Maintenance</td>
<td>Creative Disassembly and Precision Assembly</td>
<td></td>
</tr>
<tr>
<td>13. Proof Test for Precision Assembly Quality</td>
<td>Every task proven correct</td>
<td>Milestone Tests</td>
</tr>
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<td>14. A quality assurance system to make all above happen</td>
<td>ACE 4T</td>
<td>ITP (Inspection &amp; Test Plan)</td>
</tr>
</tbody>
</table>

NOTE: These parameters are indicative and may not apply to a particular machine. Confirm actual requirements with the manufacturer.
Precision Maintenance is a set of activities performed by the maintenance crew and operators that produce highly reliable machinery. It requires the achievement of very high standards and tolerances, combined with critical observation and assessment skills to identify and remove potential failures.

Introducing Precision Maintenance requires training in best-practice precision skills, supported in the workplace by a top-class engineering ‘body of knowledge’ including machinery and maintenance standards. If you want equipment in your operation at consistently high reliability, the maintenance and operations people need to develop higher work skills and quality practices that they do not yet have. To develop those skills requires setting high levels of excellence and then training people to them. Many managers, operators and tradespeople will not believe they need such high skills in their operation. This of course is a fundamental error in their thinking. They do not realise that their current processes are not capable of delivering the reliability they want, and explains why many businesses that are busy with improvement efforts still suffer poor availability and breakdowns; they are improving practices that have naturally wide ranges of outcome. Providing tradespeople with a tension wrench to tighten fasteners has little effect on the number of loose and snapped fasteners. If you require tension in fasteners to be accurate to ±10% and provide your people with a process that delivers ±25% variation, there is no chance of consistent success.

The last item in the list of key Precision Maintenance requirements is the glue that keeps the rest together. It requires installing a business process that ensures the other requirements are delivered to every machine and equipment item in the operation. The solution is to use the Accuracy Controlled Enterprise procedural tools to turn precision into standardised procedures. With ACE in place you have the tool to drive amazing equipment reliability and production results. You solve equipment performance problems forever. And, more importantly, it lets you make Precision Maintenance a habit throughout your operation. In a nutshell introducing a Precision Maintenance Program consists of:

- Corporate approval to implement precision maintenance and precision practices
- Agreement across the operation on the plant and equipment to be precision maintained
- Agreement across the operation on the precision standards to use for the plant and equipment
- Agreement across the operation on the best practices to be applied to meet the standards
- Agreement across the operation on the measurement methods that will prove compliance to standards
- Writing ACE 3T procedures for all maintenance and inspection activities on the selected plant and equipment
- Conducting a gap analysis to identify necessary test equipment, specialist tools and facilities
- Identify any needed skills to be learnt by on-the-job training and expert support
- Applying the ACE 3T procedures and refining their use
- Monitoring the effect of the program on plant performance
- Continually improving the use of precision skills and practices
- Expanding the program to other plant, equipment and sites
Standards for World Class Equipment Reliability

“Only world class standards can produce world class results.”

If you want precision maintenance reliability, you will need to bring your peoples’ machinery skills and engineering knowledge right-up to the level where they can deliver world-class machinery performance. This is what the ACE 3T procedural tool does for you. For Precision Maintenance to work it needs your shopfloor people and maintenance supervision to want it and to learn the necessary new skills. It requires the right engineering know-how and knowledge in the workforce, it requires procedures used in a very specific way to provide statistical quality control of maintenance work. When done properly you will maximise production for little maintenance cost.

Though your shopfloor people deliver Precision Maintenance, it is Maintenance and Operations Managers who start the change, sustain it and keep improving it. The great problem for industry is to find a reliable way to introduce the necessary changes in working practices so that precision thinking becomes the natural way to work. The journey to Precision Maintenance success needs a sound, safe and encouraging method to change the way people work. There needs to be a safe approach for maintainers to gain understanding of Precision Maintenance – its work quality requirements, the skills needed, and the procedural methods to make Precision Maintenance work for the operation.

Starting Precision Maintenance requires a well thought-out and structured change management process that gets your people to want to introduce, and work to, new higher-skilled meticulous practices.
Using Precision During Maintenance

Precision skills come into play –

- in the disassembly of equipment for maintenance and corrective work. It is when the information is gathered to identify the root causes of failure and to provide feedback information contributing to redesign to eliminate failure and unnecessary maintenance.
- during reassembly and repair of equipment to ensure quality work takes place; attention to fits and tolerances, fitting of bearings and other components etc.
- during installation to ensure foundations and substructures are sound and highest alignment standards are met.

The process of moving **Toward Improved Plant Reliability** through Precision Skills requires a significant change in attitude and thinking at all levels in the maintenance organisation.

A Change in Philosophy…

FROM detecting problems and fixing them, which is REACTIVE.
TO preventing failures from happening in the first place, which is PROACTIVE.

Good is no longer good enough – excellence is to be expected.

Most machinery problems are preventable.

Everyone in the organization has a role.
You will even have to go as far as ensuring every tool used in your operation can be trusted whenever it is used. You will need to set standards for the tools your operators and maintainers use so that they do great work every time.
Each of these pictures of failed bearings tell the story of what caused its demise. When bearings are removed look at the ‘story they tell’ before throwing them into the bin. You will very likely be able to find the cause of the failure and fix it while doing the job.

Creative Disassembly – Pre-shutdown of Equipment

Gather historical and background data whilst still in service …

- vibration, bearing, thermography, oil data for diagnostic purposes. Look at this for varied process conditions
- check for running ‘soft-foot’ (machine distortion when at operating under load)
- look for resonance in machine, structure, pipe work, other attachments
- look at the equipment’s maintenance history for tell-tale evidence

Thanks to Peter Brown of Industrial Training Associates for the slide
Improving machinery reliability starts with knowing where its current problems are. That information can be found from the equipment’s history and by collecting evidence of its poor performance and condition while it is running.

Creative Disassembly –
At Shutdown

**Before Strip-down …**

- where thermal growth is important for alignment, obtain hot alignment readings while still at operating temperature
- look for witness marks, evidence of shifts or relative movement
- check for static soft foot (machine distortion when at stand-still)
- sample lubricants and other fluids

Creative Disassembly –
At Strip-down

- Look for witness marks, evidence of fretting etc
- Disassemble in clean and well lit areas
- Photograph damage if applicable
- Avoid damaging during removal
- Mark the relative locations of bearings in housings, top and side, inboard and outboard
- Gearing wear patterns - eccentricity, backlash, misalignment etc

**Inspection of bearings …**

- when removed, prior to cutting
- cut the cage/retainer rather than springing it
- cut outer race from top centre to bottom centre
- re-inspect prior to cleaning
- filter solvents to see what is in the bearing
- analyse bearing and ball path patterns
- spalling patterns revealing poor fitting
- fitted surfaces revealing fretting, out of roundness etc
When the equipment is shut down look for evidence of abnormal operation and condition. As the machine is stripped down look for evidence in its parts and assemblies for signs of what has been happening to it during use. Every part ‘tells’ us the story of its life, if we look for it.

That’s how maintainers deliver Precision Maintenance, Ted. We use all of our know-how, expertise and inquisitiveness, along with the necessary technology, to understand what happens to the equipment when it’s in operation, and then we rebuild it so that it experiences least stresses and degradation when it’s working.

How do you know that you have done precision work?

As the day’s session draws to a close …

Precision proves itself. First you make sure all the ‘Tests’ in the ACE 3T procedures used to strip, rebuild and install were 100% correct. Then as a final check on your workmanship you use condition monitoring to prove the precision standards were met, or bettered.

So first we do quality work, then we use the same equipment that tells us that we have a problem, to tell us we have rebuilt, installed and got the machine running precisely?

Why not? If we have improved our machine we will see it with our condition monitoring in the start-up results. The results will all be in the ‘sweet spot’.
Using Condition Monitoring to Optimise Availability

Condition monitoring is not only a tool for checking the equipment condition. It is equally as valid to use it to improve the machine conditions.

You can use condition monitoring to get higher equipment reliability and higher plant availability. Condition monitoring is a tool to gather the information you need to focus your efforts in increasing reliability. An example is when rebuilding machinery test that the workmanship was to the required standards by checking vibration levels at bearings and making sure they are very low vibration values. Through perseverance you will in time you improve the knowledge and work quality of people, so they learn how to deliver plant and equipment in excellent condition.
A Roadmap for Reliability Improvement

This is a good overview of what we need to do with our plant and equipment throughout its life cycle. If we want high reliability in operation we need to have high reliability at every stage of a machine’s life.

The slide is from Vitech in Australia. It presents a simple and complete approach to increasing machinery reliability. It provides focus and recognises the interconnection between the important factors that affect the equipment life cycle. It indicates the important things that must be done in industrial plants to achieve operating and maintenance excellence that produces world class availability.
Your maintenance methodology and practices need to progress to including the additional stages shown in the slide, if you want to get ultra-high reliability from your plant and equipment. Risk management and Quality Management needs to be woven into everything done in maintenance.

The added boxes are the natural requirements for the progressive businesses of the future. Costs are continually driven-out of the business by people with a passion for mastery over their operating equipment and their duties. They are ‘continual learning and doing’ experts in their field. They push the limits by using and improving world best practices in risk control and work quality. They monitor how the methodology and practices they use affect the business. They support and encourage those approaches that deliver the most value to the business.

This is the world of zero failure!
Ted, it’s now time to move into the actual day to day work of the Maintenance Planner. These past few days were meant to give you a good understanding of why we have maintenance and the role it plays in ensuring maximum production for the least cost. Next time we meet we’ll start you learning the Maintenance Planning process.

What process? Isn’t it just scoping out the work and ordering parts?

Ahh … you young guys think you know it all! No, what you say is the smallest part of the job. The big part is making sure things go right the first time! And for that you need a process, a system!

The sessions on Maintenance and Reliability end …

End of Day 1

What’s on in Day 2

• Planning Maintenance Activities
• Planning Systems
• Maintenance Job Standards
• The Planning Process
• Project Management

1. Work Identification
2. Plan Work
3. Schedule Work
4. Record History
5. Execute Work
6. Analyse for Improvement

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9. Index

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