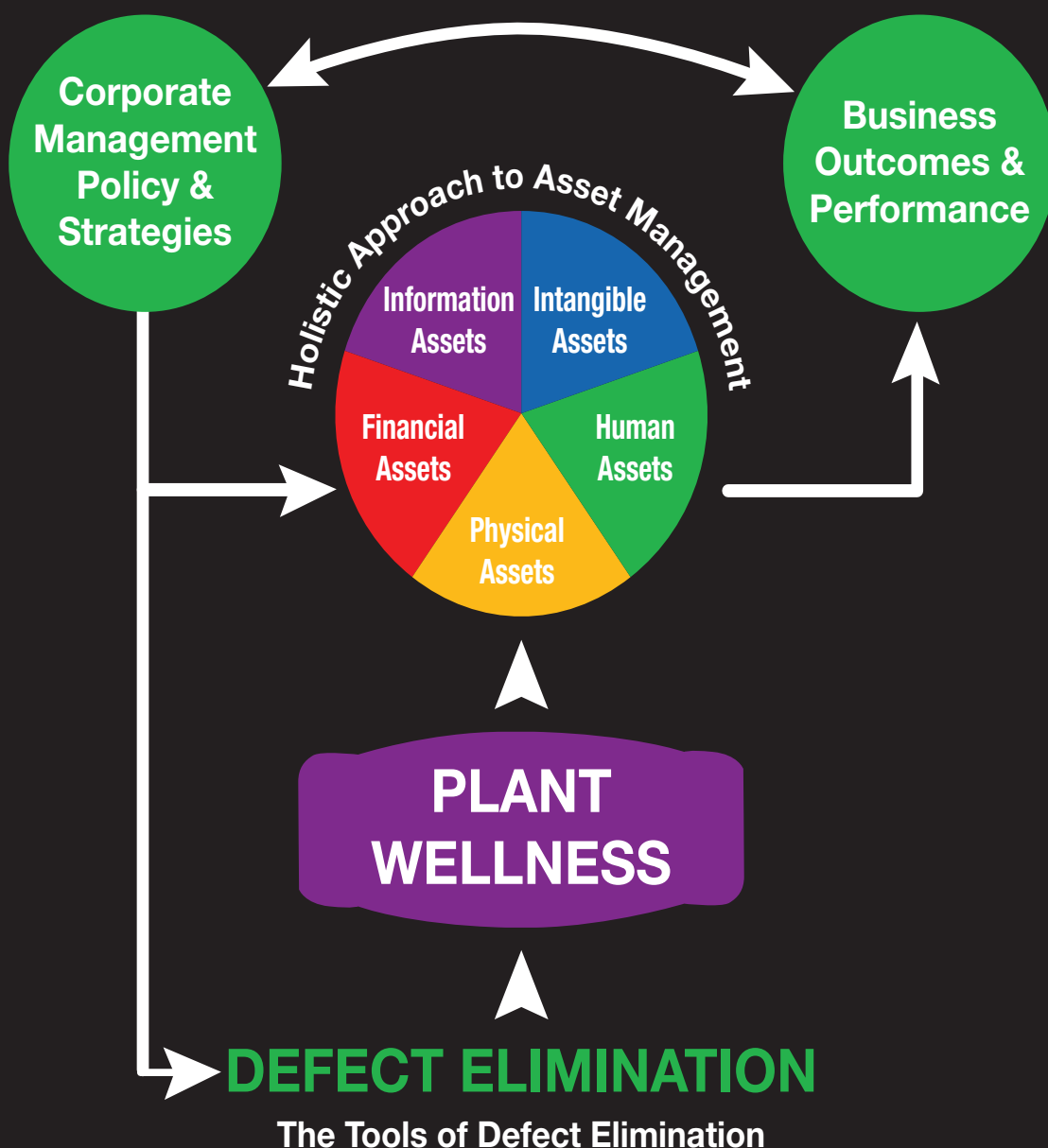


# PLANT AND EQUIPMENT WELLNESS

A Process for Exceptional Equipment Reliability and Maximum Life Cycle Profits

Mike Sondalini



# Plant and Equipment Wellness

*A Process for Exceptional Equipment  
Reliability and Maximum Life Cycle Profits*

**Mike Sondalini**



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# Contents

Preface.....	vii
Introduction .....	ix
<b>PROCESS 1 – Operating Risk Identification .....</b>	<b>1</b>
<i>Description of Process 1 – Risk Identification .....</i>	<i>2</i>
1. Reliability of Processes .....	3
2. The Physics of Failure.....	16
3. Variability in Outcomes .....	24
4. The Instantaneous Cost of Failure .....	44
5. Preventing Life Cycle Risks .....	61
<b>PROCESS 2 – Operating Risk Rating .....</b>	<b>73</b>
<i>Description of Process 2 – Risk Rating .....</i>	<i>74</i>
6. Pathway to Plant and Equipment Wellness.....	75
7. Defect Elimination and Failure Prevention .....	86
8. Operating Equipment Risk Assessment.....	107
<b>PROCESS 3 – Select Operating Risk Controls .....</b>	<b>121</b>
<i>Description of Process 3 – Selecting Risk Control Strategy.....</i>	<i>122</i>
9. Use Process Maps to Identify Risk and Improve Reliability .....	123
10. Failure Mode Effects and Criticality Analysis.....	127
11. Chance Reduction Risk Management .....	133
12. Selecting Maintenance Strategy for Risk Management .....	141
<b>PROCESS 4 – Introducing Risk Control .....</b>	<b>151</b>
<i>Description of Process 4 – Introducing Risk Control .....</i>	<i>152</i>
13. Organisation Structure and Teams (A Reliability Based Model).....	154
14. The Accuracy Controlled Enterprise .....	163
<b>PROCESS 5 – Operating Risk Monitoring and Measuring .....</b>	<b>185</b>
<i>Description of Process 5 – Risk Monitoring and Measuring .....</i>	<i>186</i>
15. Process Step Contribution Mapping.....	187
16. Key Performance Indicators .....	208
17. Mining Your Maintenance History .....	221
18. Reliability Growth .....	240
<b>PROCESS 6 – Operating Risk Continual Improvement.....</b>	<b>253</b>
<i>Description of Process 6 – Continual Improvement .....</i>	<i>254</i>
19. Failure Root Cause Removal .....	255
20. Precision Maintenance Skills and Standards.....	263
21. Change Management for Workplace Innovation .....	269
22. The Plant and Equipment Wellness Vision .....	272
Glossary .....	275
Bibliography .....	295
Index.....	297

# Preface

What are the answers that bring enterprise asset management success? I have looked long and wide for them since the early 1990s. I knew they existed. There were companies and organisations renowned for their operational excellence, exceptional equipment reliability and low production costs. Such operations were, and still are, a tiny minority. It is not easy to be the best. I have since learned that ratio is normal; though totally unnecessary. I was fifty two years old when I finally realised what maintenance and asset management were meant to deliver to a business, and how it could be done. That education took me nearly two decades to assemble. Many times I wished that there was one place where I could go to find what was important to know and understand to be a world-class operation. That is why I wrote this book. Equally important to me was to speed the whole process of becoming world-class. No company can afford to wait decades while its managers, supervisors and engineers learn what to do. Even three years is too long. The second purpose of this book was to present a standard methodology to integrate maintenance and asset management best practices throughout a business.

When you write a book on creating maintenance and asset management excellence, you soon realise how much of your thinking is based on what you have read and learnt from previous people's work. Few of the recommended practices and methodologies promoted in this book are my own. Most are the good sense and proven methods of others. Amongst them I have added some new ideas based on my industrial experiences, to provide the missing links that I believe are needed in a standardised process for achieving equipment reliability excellence and maximum life cycle profit.

There are several people to thank who helped me get this far in my never-ending journey of learning and understanding. They provided insight and knowledge that I would have never found without them. Thanks to Raymond Ho at the Swan Brewery, who first showed me the value a great maintenance and reliability professional brings to a business; Peter Brown, from Industrial Training Associates, for the wisdom gained from his many more years of dealing with people and machines in industry than myself; Max Wishaw, for the encouragement to trust myself, and retired Maintenance and Reliability Professor David Sherwin, whose thorough knowledge and no-nonsense approach made me question all that I thought was right, and thereby made things clearer to me.

This book would never have been written without several other people who put up with me. They include Robert Barber and the people at Engineers Media, for whose persistence I will always be indebted; the mysterious reviewer of the first draft copy of the book who liked what was written, even though it was so poorly expressed (and sadly still is), and my wife Susan who lived with years of me typing articles and drawing diagrams that kept me secluded from family life.

There is another group of people to thank, but whose names are too numerous to list, or are now distant memory. It is those people across the world of maintenance, reliability, quality

and asset management who so willingly and dedicatedly shared their experiences, ideas and knowledge with me through their books, articles, discussions, conference presentations, seminars and training courses. You have all helped me to new thoughts and corrected my wrong thinking.

Without doubt I have errors and misunderstandings in this book. As David Sherwin points out in his seminars, “Enterprise Asset Management is a developing discipline still full of theories not yet proven.” I am sure that many of my own ideas will not last long before better methods are found. That is my third hope for the book, that it drives improvement in our understanding of what really does work in making organisations into world-class operations – so then we can all get there.

*Mike Sondalini*

# Introduction

Welcome to the Plant and Equipment Wellness Methodology. Wellness is the journey to finding personal health and well-being. It encompasses discovering the right balance of the mental, physical, emotional and spiritual elements that make our life ideal. Wellness, and the health it brings, is also a wonderful concept to apply to our operating plants and machines. The four constituents to be balanced to get plant wellness and long-term equipment health are capital, culture, people and processes. Processes correspond to the mental, capital the physical, culture the emotional, and people the spiritual element of human wellness.

A prime purpose of this book is to provide a standardised way toward world-class reliability and asset performance. I have adopted W. Edwards Deming philosophy of presenting a proposal to be tested, and by the testing learn how to improve it. This book provides a methodology to maximise plant and equipment reliability that moves an organisation toward operational excellence through 'plant wellness'. Whether you are one person, or a large multi-national group, this book aims to deliver maintenance and reliability success to every user. It is a foundation document for those organisations that use plant, equipment and machinery assets. Included with the book is a CD that contains sample spreadsheets used in the methodology, and a teamwork manual to help introduce the business-wide processes needed of a world-class operation.

Many people will say that there are other ways, simpler ways, to become world-class. It may be so. Whether a methodology is hard or easy is not important; what is important is that it works! Plant and Equipment Wellness is a system of processes to produce sound operating and maintenance strategy and introduce best reliability practices into a business. It is a pathway to becoming amongst the best in the world at getting plant and equipment reliability. Becoming the best requires thinking, planning, systems development, practice and continual improvement. This methodology lets you identify exactly what to do to get maximum equipment reliability, and helps you to do that expertly. Read the book first to gather the concepts it contains. Read it a second time to put the concepts into mental order, and understand their interplay. Use it a third time to map the changes necessary in your operation for it to become a world-class performer.

Plant and Equipment Wellness depends on three key premises. The first is that equipment can only be failure-free if its individual parts do not fail; nothing else matters if the parts break. Parts fail first and then equipment stops. The health of equipment parts fatally impacts equipment reliability. Take care of the parts and the equipment cannot help but be exceptionally reliable. This premise is the cornerstone of production and maintenance success and its achievement will liberate great wealth.

The second premise is that people operate plant and equipment. People introduce 'human factor' and human error issues that can destroy equipment reliability, such as their degree of competence, interest in doing better, amount of curiosity, level of dedication, desire to learn more, and many other entirely normal human traits. The better the 'human factors' are

managed and developed, the more successfully and failure-free will equipment run.

The third premise is that we are working to build a world-class business. A business built of reliable processes that produce desired results which stakeholders and customers are delighted to have. Poor plant and equipment reliability is a business process failure that prevents business success. The more precisely that plant and equipment are used and maintained, the less is the risk of failure, the higher is the quality, the lower is the product price, and the shorter is the delivery time. Customers like that and will buy your product, so making the business successful.

Parts, people and processes; machine, man and method; these are what make our products and services. Each is important to business success and must be encouraged to perform at their best.

Figure i represents where Plant and Equipment Wellness sits amongst the methodologies available for reliability growth, and shows the direction that it aims to take a business.

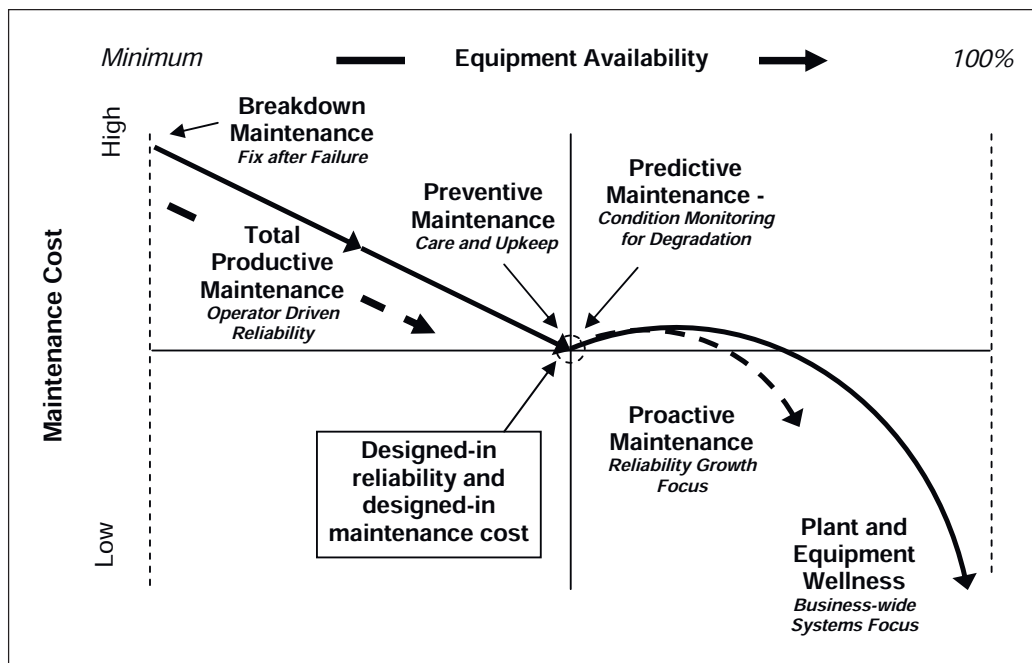


Figure i – The Journey to Plant and Equipment Wellness.

Ensuring equipment parts are always in good health is Maintenance Management. Developing systems and processes that ensure people and equipment work well together for the benefit of the business is Enterprise Asset Management. Maintenance focuses on the parts; Enterprise Asset Management focuses on the work processes and the people. The size of your operating profit is the measure of how successfully each is applied. The Plant and Equipment Wellness Methodology combines maintenance management with key elements of enterprise asset management, and adds Lean business process improvement, work quality management and continuous improvement, to produce a systematic and complete approach to getting the best performance from your parts, people and processes.

You can only do world-class work when you understand it fully and you are its master. This book is both an educational tool and a system for achieving world-class asset management. It includes education for its users in what to do and why. You can simply follow its recommendations, but you will have greater satisfaction if you know why what you do works. You are then the master and can apply your knowledge and know-how anywhere to produce



the right results. The book will help you to create a world-class system of plant and equipment reliability. World-class is defined as ‘the best there is’. With the systems and processes you develop and build using this methodology, you will move your operation toward world-class performance. Figure ii is a simple flow diagram of the methodology. It shows the six process steps to create a lifetime of highly reliable plant and equipment. Work through them one after the other. Nothing that you will do in the methodology is difficult. But you must do it. If you do not, you cannot have the results that this methodology can deliver.

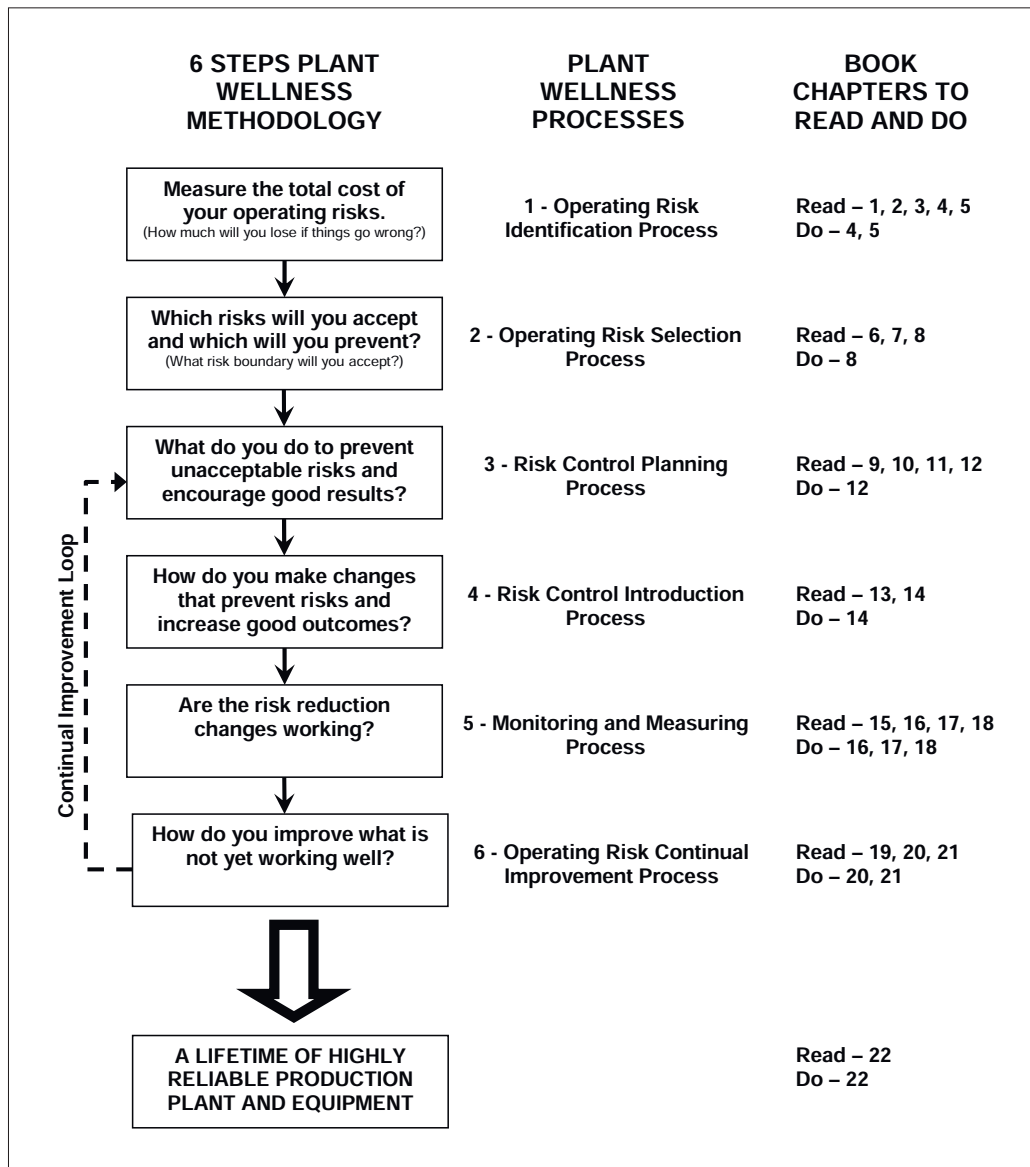


Figure ii – The Plant and Equipment Wellness Maintenance Methodology.

The first purpose of maintenance is to deliver equipment reliability. But you need to know what reliability is before you can ever hope to deliver it with your business systems, methods and practices. Businesses and machinery are series processes and there are only two ways to get high reliability in a series process – exceptional inherent reliability and parallel redundancy. The book starts by simply explaining the basics of series process reliability and the ways it is improved.

The book then moves onto understanding the second purpose of maintenance – risk control. Use maintenance to prevent things from going wrong with production plant and equipment; not to fix failed things. The greater the number of risks you chose to live with, the more failures there eventually must be. You minimise equipment failures by meeting best engineering quality standards, applying stress-reducing operating practices, and by designing-out risks all together.

The greatest risk to high equipment reliability and operational excellence is during the feasibility and design phase of the life-cycle. At this stage, decisions have permanent effects on the number and size of an operation's future risks. The design sets the operational costs. If you want an operation with few problems and low costs, you must make low-risk decisions at design. Once the equipment is in place and operating you are stuck with it. During operation you are limited to only good operating practices and good maintenance practices as risk management strategies. When you design a new plant you are also designing a business. If the original design choices were poor, you will need to revisit them during the operating phase of the life-cycle and correct the design errors.

The next section of the methodology helps you build a maintenance system with the right focus and the right activities that in a short time delivers highly reliable equipment with minimal chance of production losses. You will work through the financial, work management, people management and continual improvement processes you need to have in-place and, most importantly, in-use to create world-class production performance. Along the way, you learn a variety of maintenance management methods, physical asset management approaches, lean thinking and quality system tools to control your equipment reliability and ensure it delivers the world-class results that you want.

Remember that you are building a great business that makes and delivers a great product. For those who want to be in the best of businesses, this methodology is the ideal starting point to develop your engineering asset management and maintenance management systems.

Figure iii is a stylised overview of how a business applies Plant and Equipment Wellness to manage the engineering assets in the business. Take the first step to world class performance and understand how world-class reliability is achieved; good fortune awaits you!

*Mike Sondalini*  
*[www.lifetime-reliability.com](http://www.lifetime-reliability.com)*

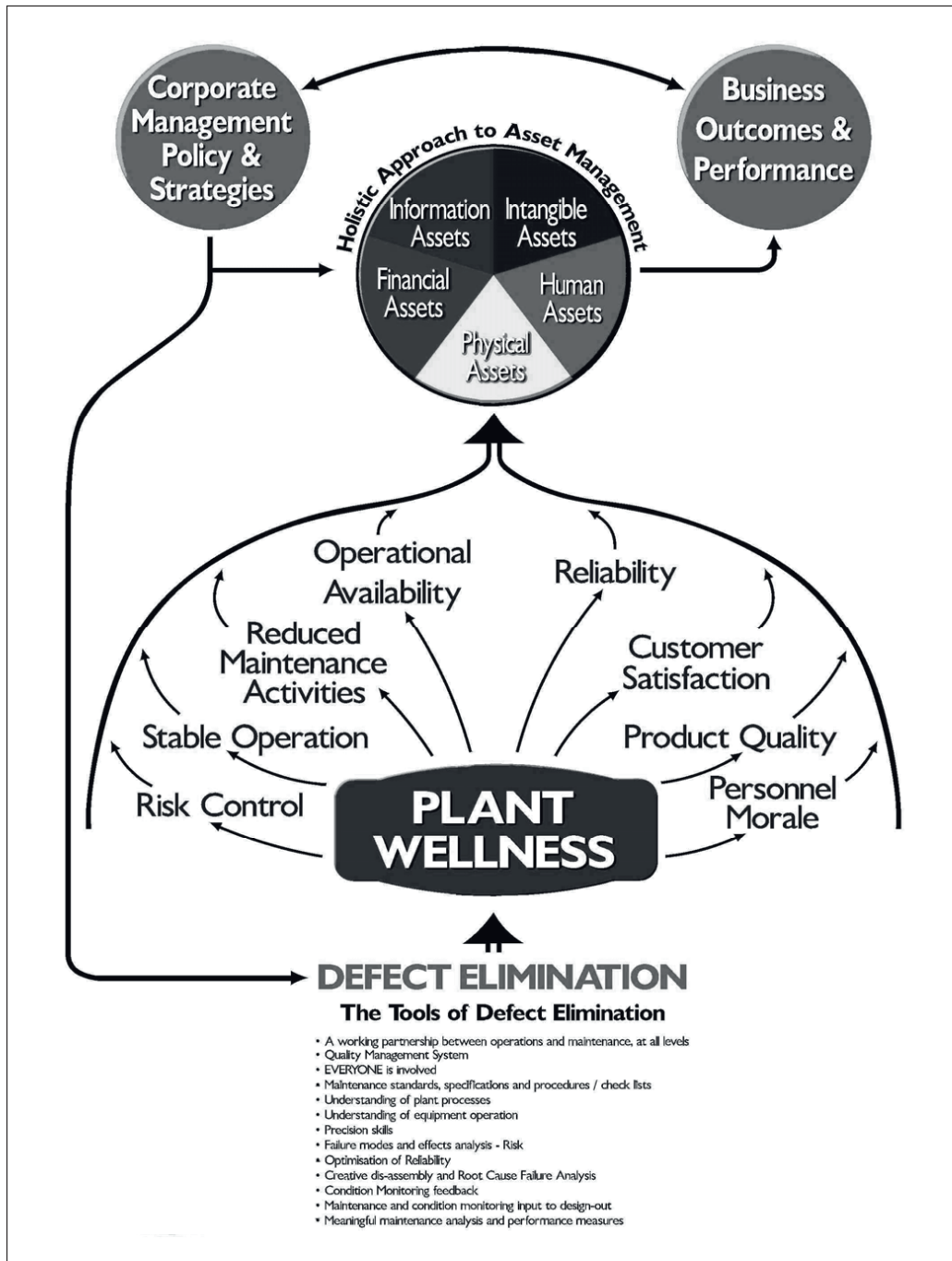
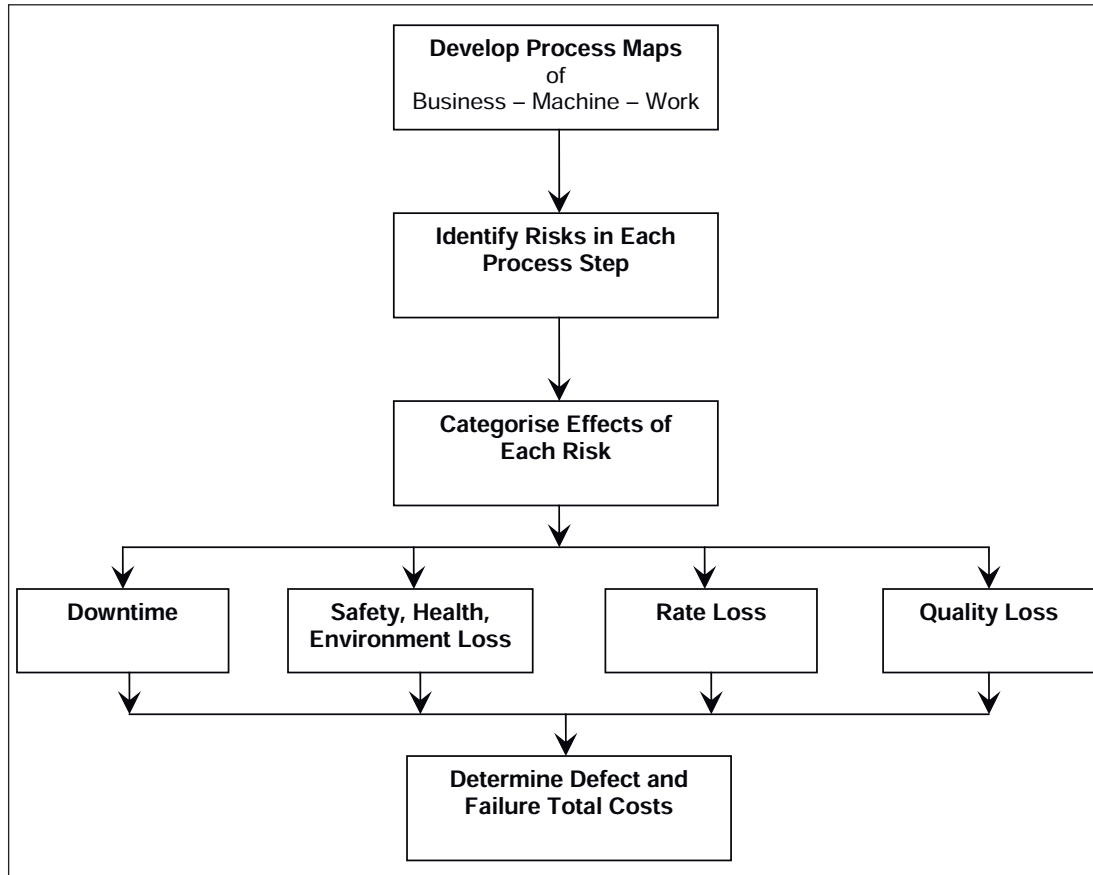


Figure iii – The Purpose and Benefits of Plant and Equipment Wellness.\*

\* Thank you to Peter Brown of Industrial Training Associates for the Plant and Equipment Wellness concept.

# PROCESS 1 – Operating Risk Identification



## **Description of Process 1 – Risk Identification**

### **Develop Process Maps**

Start the Plant Wellness Methodology by making process maps of what you are analysing. The process map is the foundation for building a highly reliable operation. They show the design logic of the process. These simple boxes and arrows joined together across the page are a powerful visual tool for understanding how a system, machine or work process operates. With a process map you will do a better job of analysing process weaknesses and areas of risk. They allow you to see the interconnectivity within processes, across processes, and the impact of each step's reliability on the process outcome. Later they help you to design a better process and to create key performance indicators to monitor and measure process improvements. You will use them to explain to others the reliability improvements needed, why they will be effective, and how to implement them.

### **Identify Risks in Each Process Step**

From the process maps develop a spreadsheet that records every process step. If the process is an item of equipment or machinery, list all its assemblies down the page in logical order. For an assembly list all its parts in sequence. Leave nothing out of the list. You will not get full protection from equipment failure if all parts are not fully analysed. If it is a production line, include all production equipment in the process map in order of product flow. For a work process, list all the activities in sequence. Give each item in the list its own row in the spreadsheet. The spreadsheet expands for other uses during the analysis. An example of such a spreadsheet for production equipment is the 'Risk Identification-Grading' worksheet provided on the accompanying CD to the book.

### **Categorise Effects of Each Risk**

Taking each item listed on the spreadsheet in order, identify its known and possible (i.e. might happen during the equipment's lifetime) failure causes. A failure is any incident or problem that affects quality, production rate, health / safety / environment (SHE), or causes downtime. Record all causes on the spreadsheet against the item.

Against each cause, indicate its cost and the effect on the operation, its people and environment. This list is later used elsewhere in the analysis.

### **Determine the Defect and Failure Total Costs**

For each failure cause, calculate the Defect and Failure Total Costs. The DAFT Cost is the company-wide cost surge that every failure produces across a business. They total far more than the cost of repair. If you cannot calculate the full DAFT Costs using the method described in this book, calculate the direct maintenance cost of repair and multiply that figure by 10 for continuous processes, and by 5 for batch processes. This factored cost is indicative of the surge costs that every failure causes a business.

## 1. Reliability of Processes

A business must work on paper before it can work in reality. From a collection of interacting processes a business produces products and services. Every activity is part of a process chain. The performance of each process depends on how well each activity is done, and the performance of the business depends on how well each process is done. One activity done poorly makes a process poor, one process done poorly weakens the business. The physical, financial, human, information, and intangible processes that make-up a business need to work in concert for the business to thrive. With all activities done to world-class quality, a world-class business results <sup>2</sup>.

### Asset Life Cycle Impacts

To understand how business and work processes impact equipment performance we must see the interconnectivity of the processes used to buy, make and run equipment. If processes can go wrong in your operation, they can go wrong in everyone else's operation too. Figure 1.1 shows a simple process used to make a product.

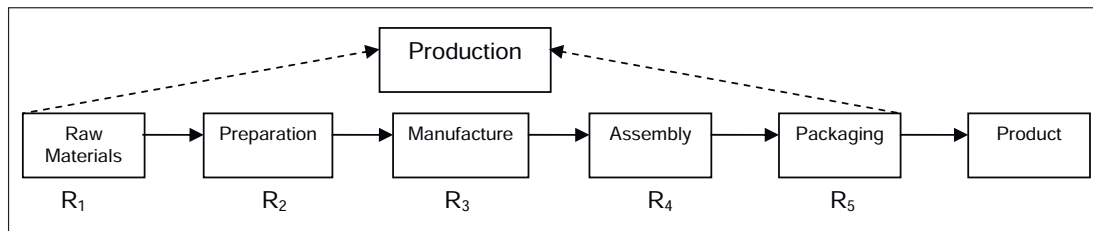


Figure 1.1 – A Series of Steps in a Production Process.

Within each box of the production process chain are other process chains. The Raw Material step will have numerous processes impacting it, the Preparation step will have its processes, as will the Manufacture step and so on for all of them. Figure 1.2 shows some of the processes

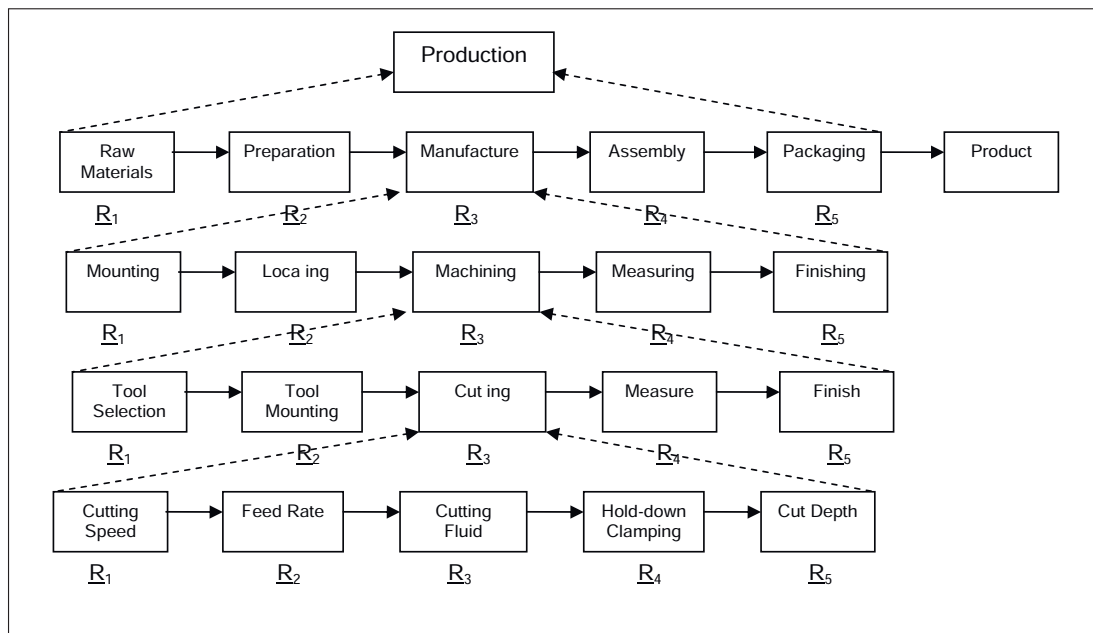
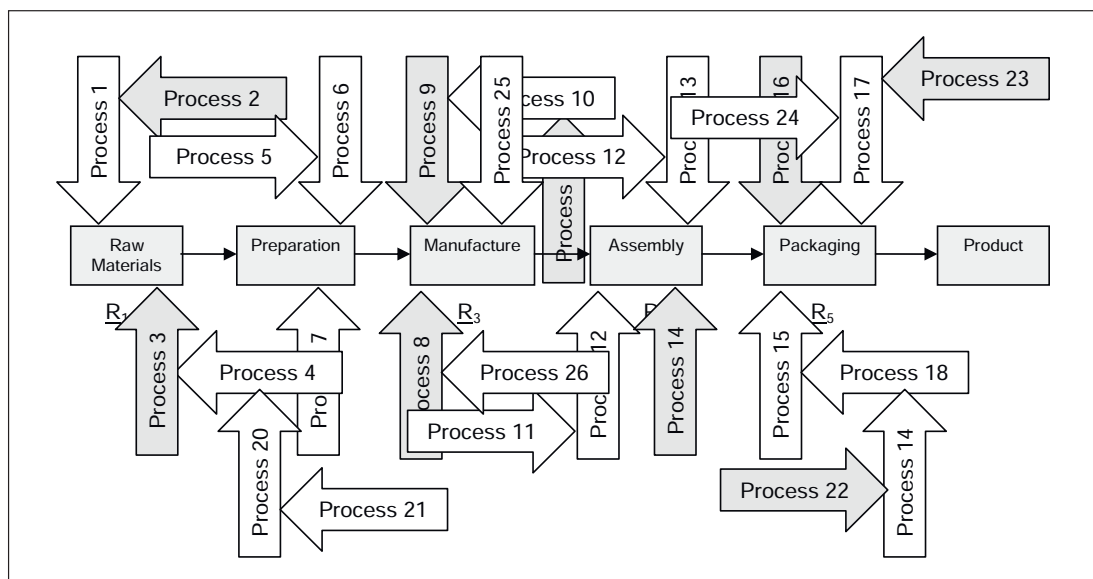


Figure 1.2 – There are Numerous Work Sub-Processes in Every Production Process.

<sup>2</sup> Feigenbaum, A.V., 'Total Quality Control', Third Edition, MacGraw-Hill.

in the Manufacture step. There are hundreds of activities in dozens of processes affecting the operation. Figure 1.3 is a representation of the many business processes involved in making a product.

Process after process connects with others in a tangled web of interaction across time and space. There are dozens and dozens of them, each one containing task after task. There are hundreds, if not thousands, perhaps even tens of thousands of tasks in some businesses. Each one is an opportunity for things to go wrong. Because each process feeds many other processes, any error in one has a knock-on effect that harms those downstream of it as well. Any process that goes wrong impacts numerous others in future. For example, a poor maintenance repair will cause a future production failure; an operator error that overloads a machine will start a future breakdown; the wrong choice of materials of construction by a gas processing plant designer contributes to a future explosion and the death of people. That is why it is important for every step in a series process to go right every time – the future consequences are unforeseeable and may be devastating.



*Figure 1.3 – Numerous Processes Interact across Every Process Chain.*

Doing hundreds of processes and tens of thousands of activities perfectly requires a standardised system of excellence to follow. Without ensuring excellence in every process step, you cannot get excellent products or service. This is the seemingly impossible challenge in running a business well – getting the individual tasks in every process 100% right, the first-time.

If you want an operation where good results are natural and excellence abounds, you need to ensure every step in every process goes perfectly. World-class operations recognise the interconnectivity and work hard to ensure everything is right at every stage in every process. To guarantee that every activity is done correctly cannot be left to chance.

It is important to see the situations that produce failures and breakdowns in your business if you are to prevent them. This is done by drawing a map of the business processes, then finding those steps with poor reliability and improving them. Figure 1.4 is a series process map of a five task job. The process map could just as easily have been machines in a production line or companies in a supply chain. From such maps we can gauge how successful a business or a job will be <sup>3</sup>.

<sup>3</sup> Sondalini, Mike., 'Total Control Over Human Error', Australian Asset Management Council ICOMS 2008 Conference Paper.

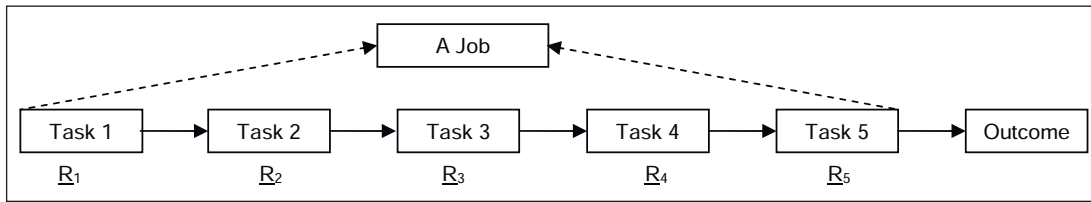


Figure 1.4 – A Series of Tasks in a Work Process.

The series forms a chain of links to a needed job outcome. Break a link and the outcome is impossible. Miss enough outcomes and your business fails.

### Work Process Reliability

Measurement of the chance of business or job success requires probability. Probability maths can get very involved, but we require only a simple level of maths to measure the chance of getting business processes and jobs right. We collect data on doing each task and then calculate the likelihood of getting the whole job right. If in Figure 1.4, Task 1 has a 100% chance of perfect work its probability of success is 1. If it is done right 50% of the time, then has a 0.5 probability of success. Equation 1.1 is used to calculate the job reliability, or the chance of doing our five-step process successfully. The underscore below the 'R' acts to differentiate the modelling of work process reliability from component or system reliability (which does not use the underscore).

$$\underline{R}_{\text{job}} = \underline{R}_1 \times \underline{R}_2 \times \underline{R}_3 \times \underline{R}_4 \times \underline{R}_5 \quad \text{Eq. 1.1}$$

We can use the equation to see the effect of human error on the chance of success in our job. A short list of human error rates applicable to maintenance and plant operating functions is listed in Table 1.1<sup>4</sup>. Routine simple inspection and observation tasks incur 100 times fewer errors than complicated work done non-routinely. Equipment repair tasks belong to the 'complicated, non-routine' category. Because they are done irregularly on complicated machinery, human error rates of more than 1 in 10 can be expected (9 times in 10 a task is done right means a 0.9 probability of success). The high human error rates for repair tasks makes breakdown maintenance and overhaul repairs very risky practices if you want high equipment reliability and production uptime. (Usually repairs are also alternated across several crew members in the questionable belief that if a person is off-work, then someone else knows what to do).

If every task in Figure 1.4 had 0.9 reliability, the reliability of the whole job would be:

$$\underline{R}_{\text{job}} = 0.9 \times 0.9 \times 0.9 \times 0.9 \times 0.9 = 0.59 \text{ (or 59\%)}$$

With 90% certainty for each task, the chance that the job is right drops to 59%. The job goes wrong 41 times out of every 100 times it is done. If this job were twelve tasks in length, its reliability would be 0.28. It would go wrong 72 times in every 100. Even if every task is perfect except Task 3, which is correct 60% of the time, the reliability of the job is still just 60%.

$$\underline{R}_{\text{job}} = 1 \times 1 \times 0.6 \times 1 \times 1 = 0.6 \text{ (or 60\%)}$$

<sup>4</sup> Smith, Dr, David J., Reliability, Maintainability and Risk, Seventh Edition, Appendix 6. Elsevier, 2005.



Table 1.1 – Selected Human Error Rates.

No	Situation and Task	Error Rate (per task)	Reliability Rate
<b><i>Routine simple tasks</i></b>			
1	Read checklist or digital display wrongly	0.001	0.999
2	Check for wrong indicator in an array	0.003	0.997
3	Fail to correctly replace printed circuit board (PCB)	0.004	0.996
4	Wrongly carry out visual inspection for a defined criterion (e.g. leak)	0.003	0.997
5	Select wrong switch among similar	0.005	0.995
6	Read 10-digit number wrongly	0.006	0.994
<b><i>Routine task with care needed</i></b>			
7	Wrongly replace a detailed part	0.02	0.98
8	Put 10 digits into a calculator wrongly	0.05	0.95
9	Do simple arithmetic wrong	0.01 - 0.03	0.99 – 0.97
10	Read 5-letter word with poor resolution wrongly	0.03	0.97
11	Dial 10 digits wrongly	0.06	0.94
12	Punch or type character wrongly	0.01	0.99
<b><i>Complicated, non-routine task</i></b>			
13	Fail to notice incorrect status in roving inspection	0.1	0.9
14	New work shift – fail to check hardware, unless specified	0.1	0.9
15	High stress, non-routine work	0.25	0.75
16	Fail to notice wrong position of valves	0.5	0.5
17	Fail to act correctly after 1 minute in emergency situation	0.9	0.1

In a series arrangement the chance of a job being done right is never more than that of the worst performed task. To do a job properly needs every task to be 100% perfect. In a series process, if one step is wrong, the whole process is wrong; if one step is poor, the whole process is poor. This applies to every series arrangement. Production processes, machines, supply chains, jobs and businesses are all at risk. It explains why production plants have so many problems – it only takes one part to fail in one machine and the whole plant stops.

Things are much worse under high stress. Such as if a maintainer is put under unrealistic time pressure, or has the wrong tools and parts to do the job properly, or is not sure how to do the job, or if their safety is compromised. By factoring the 0.25 error rate of situation 15 from Table 1.1 for a task done under stress, the 5-task job falls to 49% chance of being done right if stress only affects one task, and to as little as 24% chance if stress affects all tasks.

$$\underline{R}_{\text{job}} = 0.75 \times 0.9 \times 0.9 \times 0.9 \times 0.9 = 0.492 \text{ (or 49\%)}$$

$$\underline{R}_{\text{job}} = 0.75 \times 0.75 \times 0.75 \times 0.75 \times 0.75 = 0.237 \text{ (or 24\%)}$$

If the 5-task job is done one minute into an emergency (situation 17 of Table 1.1), there could be as little as one-thousandth of one percent chance of the job being done right.

$$\underline{R}_{\text{job}} = 0.1 \times 0.9 \times 0.9 \times 0.9 \times 0.9 = 0.0656 \text{ (or 6.6\%)}$$

$$\underline{R}_{\text{job}} = 0.1 \times 0.1 \times 0.1 \times 0.1 \times 0.1 = 0.00001 \text{ (or 0.001\%)}$$

All operating and maintenance work consists of tasks done in series processes, most of them with far more than the 5-steps of our simple example. Unless every task is done well the job is never right. That is why equipment, production processes and businesses have failures – jobs require only one error to fail them. They are failure prone arrangements. Is it any wonder that so many companies suffer from poor performing operations when their managers, engineers, maintenance crews and operators use failure-prone work processes.

## Industrial Equipment Reliability

A machine is a series configuration of parts. In a machine the parts move and act in a sequence. One part acts on another, which then causes the next part to act, and so on. If a critical part that makes a machine work fails, the whole machine stops. In plants with many items of equipment there is millions of opportunities for equipment failures and plant breakdowns.

A machine needs many processes during its building, installation and operation<sup>5</sup>. Each process has numerous tasks that have to be done right. From time-to-time mistakes and poor choices are made. Those defects eventually lead to failure during operation. An Internet search by the Author for causes of centrifugal pump-set failures found 228 separate ways for the wet-end components to fail, 189 ways for a mechanical seal to fail, 33 ways for the shaft drive coupling to fail and 103 ways for the electric motor to fail. This totals 553 ways for one common item of plant to fail. In those operations with many equipment items there is constant struggle against mountainous odds to keep them working. Improving the reliability of series processes is critically important in reducing causes of equipment failure.

In the centrifugal pump-set of Figure 1.5 an electric motor turns a rotor connected by a coupling to the pump shaft on which is mounted an impeller. For the pump impeller to spin and pump liquid the pump shaft must rotate, as must the coupling, as must the motor rotor, as must the magnetic field in the motor. All these requirements for the impeller to turn form a series arrangement. If any one requirement is missing the impeller cannot turn and liquid cannot flow.

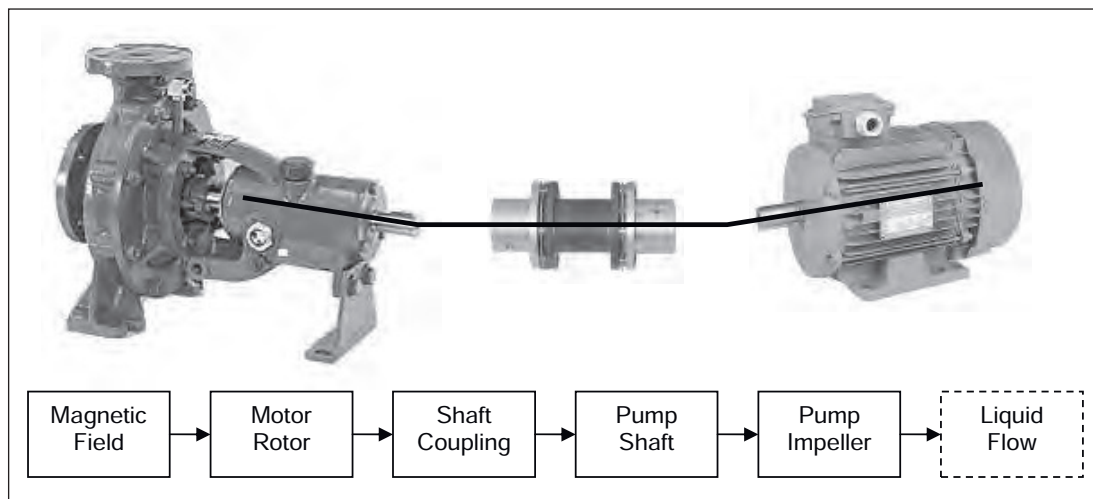


Figure 1.5 – Series Arrangement of Parts in a Centrifugal Pump-set.

One calculates the reliability of a series arrangement by multiplying together the reliability of each step in the arrangement. The equation to use is:

$$R_{\text{series}} = R_1 \times R_2 \times R_3 \times \dots R_n \quad \text{Eq. 1.2}$$

As soon as any single step in the series drops to zero, the whole series becomes zero and the system stops working. If the coupling should fail on our pump-set the impeller mounted on the pump shaft cannot turn and the pump-set is failed.

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

<sup>5</sup> Blanchard, B.S., 'Design and Management to Life Cycle Cost', Forest Grove, OR, MA Press, 1978.

**1. *The reliability of a series system is no more reliable than its 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  $0.9 \times 0.8 = 0.72$ , 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  $0.9 \times 0.9 = 0.81$ .

**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  $0.9 \times 0.9 = 0.81$ , and with three it is  $0.9 \times 0.9 \times 0.9 = 0.729$ . To return the new series to 0.81 reliability requires that all three items have a higher reliability, i.e.  $0.932 \times 0.932 \times 0.932 = 0.81$ . 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  $0.932 \times 0.932 \times 0.932 = 0.81$ , to  $0.95 \times 0.95 \times 0.95 = 0.86$ , a 5.8% improvement. 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 pay-off far more than making individual reliability improvements.

Figure 1.6 shows where series processes are used in operating plant and equipment. It highlights that series processes abound throughout equipment life-cycles. During design, manufacture, assembly, operation and maintenance, multitudes of risks exist that can adversely impact equipment performance. 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, a 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.

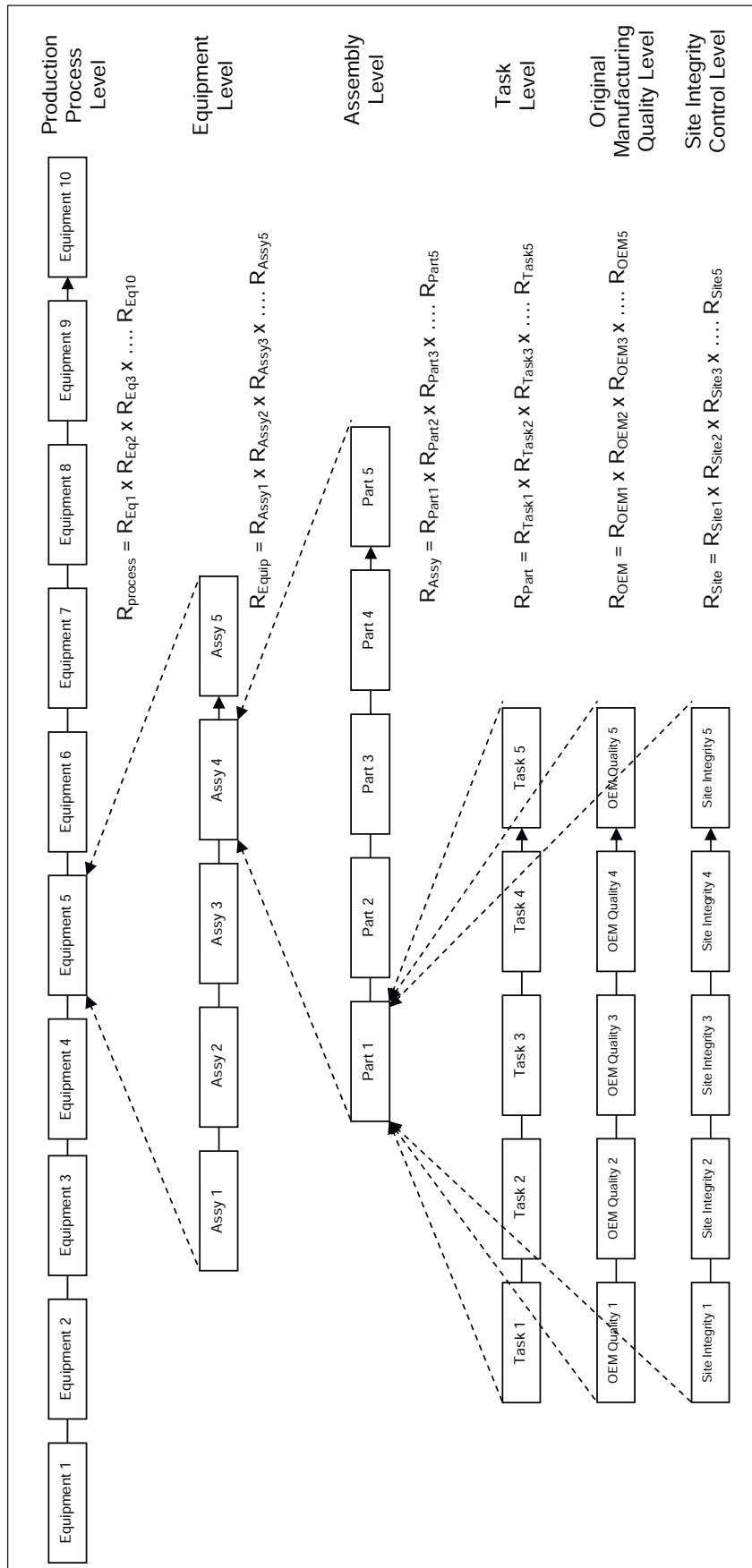


Figure 1.6 – Reliability Applies to Every Aspect of an Operation and Its Equipment throughout the Life Cycle.

### The Control of Series Process Reliability

Fortunately reliability principles also give us answers to the series process problems – the parallel process and error-proofing. Figure 1.7 shows a parallel arrangement.

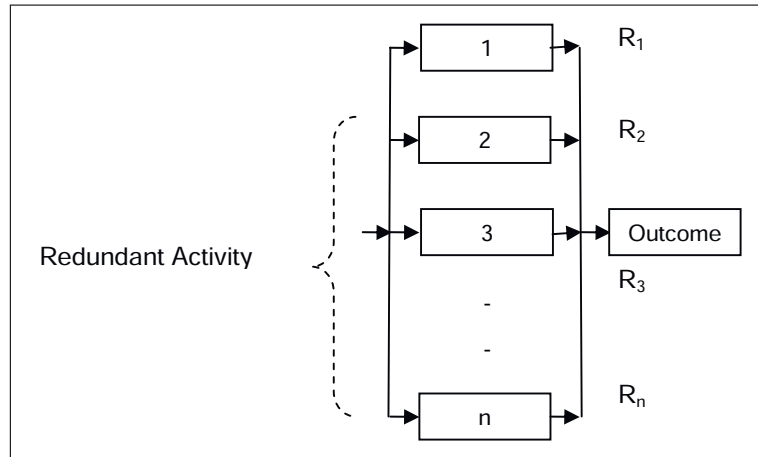


Figure 1.7 – A Parallel Process.

Reliability behaviour in parallel arrangements is very different to series arrangements. Equation 1.3 is used to calculate the reliability for a parallel arrangement where each element is in use (known as fully active redundancy).

$$R_{\text{para}} = 1 - [(1-R_1) \times (1-R_2) \times \dots (1-R_n)] \quad \text{Eq. 1.3}$$

In a parallel process of four activities, each with a poor 0.6 reliability (a 40% chance of failure), the process reliability is:

$$\begin{aligned} R &= 1 - [(1-0.6) \times (1-0.6) \times (1-0.6) \times (1-0.6)] \\ &= 1 - [(0.4) \times (0.4) \times (0.4) \times (0.4)] = 1 - [0.0256] \\ &= 0.9744 \end{aligned}$$

The parallel arrangement in the example produced 97% chance of success, even when each activity had 40% chance of failure. We can use this fact to redesign our work and production processes to deliver whatever reliability we want from them and control work error and production loss.

An example of a parallel work process is the carpenter's creed, 'Measure twice; cut once'. Carpenters know that the double-check will save problems and trouble later. The logic of the adage is the simple parallel process shown in Figure 1.8.

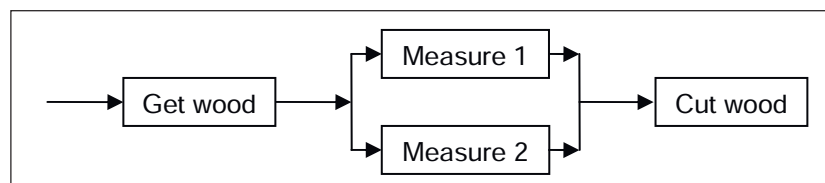


Figure 1.8 – 'Measure Twice and Cut Once', the Carpenter's Creed, is a Parallel Activity.

For a carpenter that measures once the error rate in reading a tape measure once is five times in every thousand it will be misread, or 995 times out of 1000 it will be right (a reliability of 0.995). The carpenter will cut the wood in the wrong spot about once every 200 times. It is not hard to imagine a carpenter doing 50 cuts a day. So about once a working week they would cut the wood in the wrong place and have to throw it away. When he also adds the proof-test measure the chance of getting the cut right rises to 0.9998, which is an error rate of 2 in every 10,000 times. With 50 cuts a day they will make an error once every 100 working days, or about every 20 working weeks. The simple addition of a check-test produced twenty times fewer measurement mistakes. That is the power of paralleling test activities to tasks to ensure they are right.

Figure 1.9 shows the 5-task maintenance job of Figure 1.4 as a paralleled 5-task process. Each task includes a parallel proof-test activity to confirm the task is correct; exactly like the carpenter's creed, 'measure twice, cut once'.

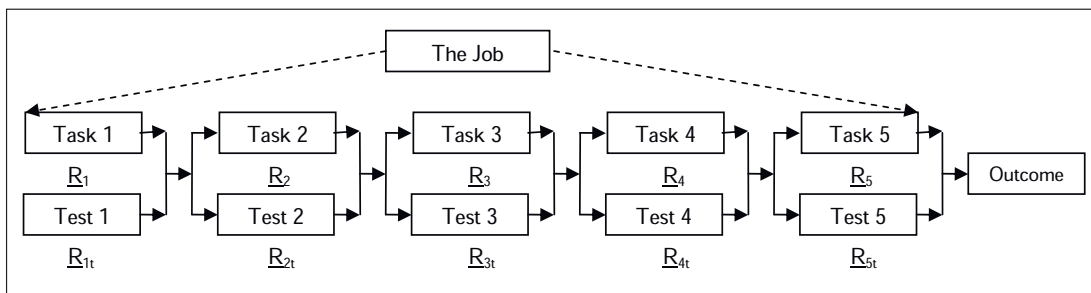


Figure 1.9 – A Parallel Tasked Work Process.

If we take the 0.9 reliability of maintenance work for each task, and for the inspect-and-measure proof-test increase it to 0.99 (because testing is carefully done using high quality tools and procedures), then the reliability of each parallel-tested step is:

$$\begin{aligned}
 R_{\text{task}} &= 1 - [(1 - R_t) \times (1 - R_{t_t})] \\
 &= 1 - [(1-0.9) \times (1-0.99)] = 1 - [(0.1) \times (0.01)] = 1 - [0.001] \\
 &= 0.999 \text{ (99.9\%)}
 \end{aligned}$$

By combining a normal task with a test activity to prove that the task is right, we create a highly reliable task. Add proof-test activities to all tasks in our 5-step job and you create a high-reliability work process. The reliability of the entire job is now:

$$R_{\text{job}} = 0.999 \times 0.999 \times 0.999 \times 0.999 \times 0.999 = 0.995 \text{ (i.e. 99.5\%)}$$

Paralleling a proof-test to each task drives the reliability for the entire job to 99.5%. But even 0.995 reliability means that 5 times out of every 1000 opportunities the job will be wrong. In a large, busy operation with many people, one thousand opportunities for error accrue rapidly. Similarly, where numerous processes are used to make a product there is hundreds, even thousands, of opportunities a day for error to happen along the process chain. We need job and process reliabilities of great certainty if we want excellence in our businesses. You can achieve this by continuing the paralleling activity with each task. Figure 1.10 is an example of what to do – continue adding protective barriers and activities in parallel. The proof-test, which involves careful inspection and/or measurement, takes a reliability of 0.99. Because 'human factors' are present in the other tasks they retain 0.9 reliability.

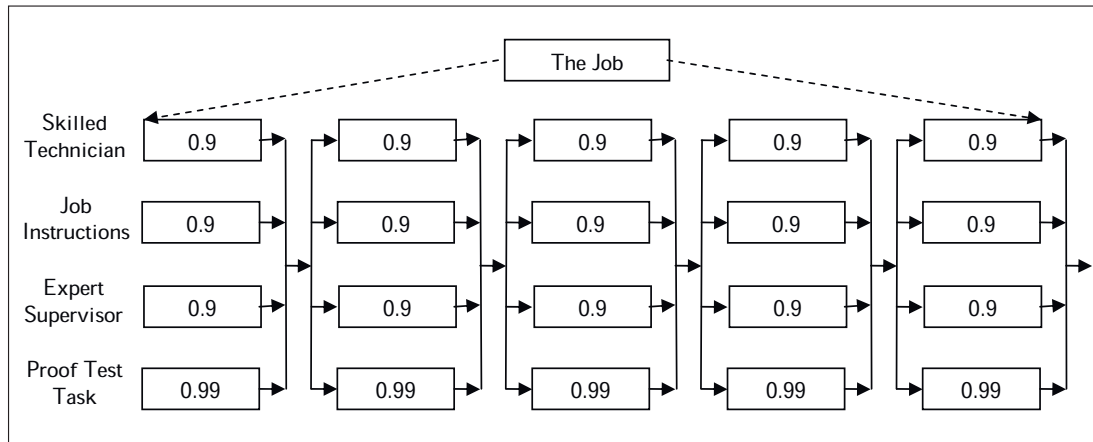


Figure 1.10 – A Multi-Paralleled Task Work Process.

The reliability equation for these paralleled work tasks is:

$$\begin{aligned}
 \underline{R}_{\text{task}} &= 1 - [(1-0.9) \times (1-0.9) \times (1-0.9) \times (1-0.99)] \\
 &= 1 - [(0.1) \times (0.1) \times (0.1) \times (0.01)] \\
 &= 0.99999 \text{ (i.e. 99.999\%, or 1 error per 100,000 opportunities)}
 \end{aligned}$$

The reliability of the entire job of five tasks with each task paralleled in error-preventing configuration is:

$$\underline{R}_{\text{job}} = 0.99999 \times 0.99999 \times 0.99999 \times 0.99999 \times 0.99999 = 0.99995 \text{ (i.e. 99.995\%)}$$

The error rate for the whole job now drops to a very low 5 errors per 100,000 opportunities. This is the way to drastically reduce work process error and get outstandingly reliable craftsmanship in every job.

You can design the reliability that you want into a job. To have high-reliability work processes build parallel inspection activities into the performance of the work. The activity of doing the work now ensures that high-reliability is the natural outcome. Make proof-testing a standard practice in the system of work; make it ‘the way we do things around here’. Parallel all critical tasks done in a job with very specific and certain error-preventing tests and inspections. Then you can be sure that the work process is able to deliver the quality you want.

My brother-in-law, who worked for Japan Airlines (JAL) at the time, tells a story of watching Japanese aircraft maintenance technicians overhaul a JAL airplane jet engine. He tells this story because it is so unusual. During his visit to the maintenance hangar he was enthralled by the extraordinary maintenance procedure that the JAL technicians followed.

He watched as a man on a podium, which was in-front of a jet engine being worked-on, read from a manual. Once he’d finished speaking, two technicians at the engine began working on the equipment. The man on the podium went and looked carefully at the work being done. When the technicians finished they stepped away from their work and the man, who seemed to be the supervisor, tested and checked their workmanship. As he went through the double-checking process he would, from time to time, sign a form that he carried. Once his inspection was completed, and the technicians had also signed-off on their work, he returned to the podium and read the next instruction from the manual. The whole process was repeated while my brother-in-law watched in astonishment.

What he saw was Japan Airlines' stringent policy of rebuilding their jet engines by following Standard Operating Procedures paralleled to verbal instruction and supervisory monitoring. The expert supervisor read each task-step, he explained it and then monitored the also fully-qualified and experienced aircraft technicians do the task. As the technicians performed the work the supervisor watched and checked their workmanship. The task was only completed when the technicians and the supervisor confirmed that it had met the required standard and a record of proof was made of its successful completion. Then the next task-step of the job was performed in the same way. By this method Japan Airlines absolutely ensured its jet engines were correctly rebuilt and fully meet specification.

If you fly Japan Airlines it is reassuring to know the rigours that their aircraft mechanics go through to ensure their jet engines and planes are in top order.

Getting the maximum reliability from processes should drive all our thinking and decision making. Build processes that are sure to produce good outcomes and results. If the reliability is insufficient for a situation, simply add another parallel testing activity to guarantee more certainty. Figure 1.11 shows how adding multiple proof test requirements creates an incredibly high reliability.

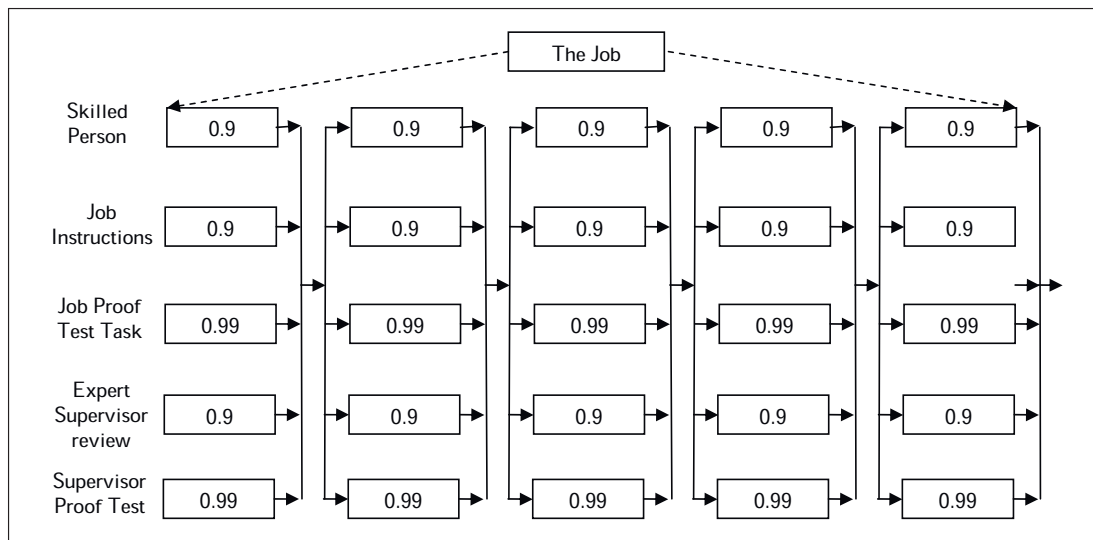


Figure 1.11 – Super-Sure Error Prevention Work Process.

The reliability of each paralleled error preventing step is now:

$$\begin{aligned}
 \underline{R}_{\text{task}} &= 1 - [(1-0.9) \times (1-0.9) \times (1-0.99) \times (1-0.9) \times (1-0.99)] \\
 &= 1 - [(0.1) \times (0.1) \times (0.01) \times (0.1) \times (0.01)] \\
 &= 0.999999 \text{ (i.e. 99.9999\%, or 1 error per 1,000,000 opportunities)}
 \end{aligned}$$

The reliability of the entire job of five super-sure tasks is:

$$\begin{aligned}
 \underline{R}_{\text{job}} &= 0.999999 \times 0.999999 \times 0.999999 \times 0.999999 \times 0.999999 = 0.999995 \\
 &\text{(i.e. 99.9995\% or 5 errors per 1,000,000 opportunities)}
 \end{aligned}$$

Should this level of job reliability not be sufficient, then continue paralleling the tasks with more tests for certainty. There is one condition to meet to get these levels of work process reliability. Each task in parallel must be independent of the other parallel tasks. For example, the 'Supervisor Proof Test' must use different test equipment to that used in the 'Job Proof Test'. If both tests used the same test device they would not be independent. Any error in the shared test equipment



will be common to both tests. Each test may pass a task when in fact the shared test device has an error. By using two independent tests one then checks the other and common error does not occur.

### The Best Answer is to Error-Proof Work and Production Processes

Human error cannot be prevented. It is in our human nature to make mistakes. They will always happen because our brains and bodies have limits<sup>6</sup>. But it does not mean that a mistake must lead to a failure. There is a better way to control failure than paralleling test activities. That is to ensure failure cannot happen by using error-proofing. Error-proofing means to change the design of a thing so that mistakes have no effect on the outcome. We get 100% reliability in an error-proofed process. In all situations and circumstances no human error leads to failure. Error-proofing does not mean mistakes are not allowed, they are inevitable; rather, when mistakes are made they will not fail the job. Examples of the practice of error-proofing equipment include changing designs of parts so they can assemble only one way, and providing parts with tell-tale indication of correct positioning. In information collection, transcription problems can be greatly reduced simply by changing the layout of forms to promote clear writing and easy reading. Figure 1.12 shows our 5-task job designed so that each task is error-proofed. The reliability of the five task job is now:

$$\underline{R}_{\text{job}} = 1 \times 1 \times 1 \times 1 \times 1 = 1 (100\%)$$

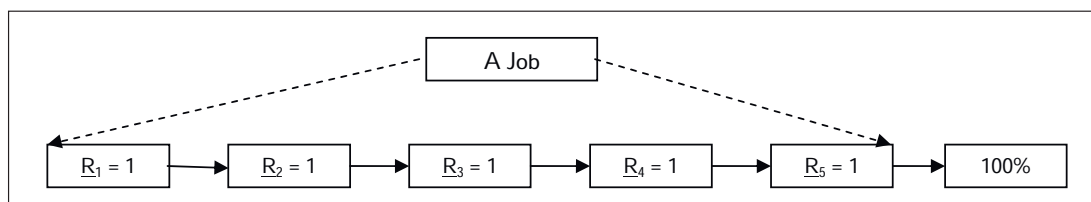


Figure 1.12 – A Series Tasked Work Process with each Task Totally Error-Proofed.

In machines designed where maintenance and operating tasks are completely error-proofed, there are no failures from human error. The work and parts are designed in ways that allow human error to occur, but the errors cannot progress to equipment or job failure. We cannot stop human error. But we can create machines and work processes that do not allow human error to cause failure. The right outcomes then result first-time-every-time.

### Improving Process Reliability throughout the Life Cycle

Figure 1.13 shows the typical life cycle of a facility. The life cycle is also a series process – feasibility, detailed design, procurement, installation, commissioning, and finally operation. There are multitudes of interconnected series work processes in every phase providing innumerable opportunities for error. By now you should not be surprised to learn that a great number of them become latent problems that play-out over time to cause equipment failures. This is why you will regularly hear maintainers cursing equipment and production plant designers for their hidden design ‘traps’. There are numerous documented investigations into safety incidents confirming that work errors occur at every stage of a facility’s life<sup>7</sup>. The reliability of the operating phase is totally dependent on the reliability of all the numerous human-dependant activities performed beforehand. Mistakes and errors can occur everywhere, at any time, in all phases of the life cycle.

<sup>6</sup> Gladwell, Malcolm, ‘Blink, the power of thinking without thinking’, Back Bay Books, 2005.

<sup>7</sup> Foord, A. G., Gulland, G., ‘Can Technology Eliminate Human Error?’, Trans IChemE, Part B, Process Safety and Environmental Protection, 2006 84(B3): 171-173.

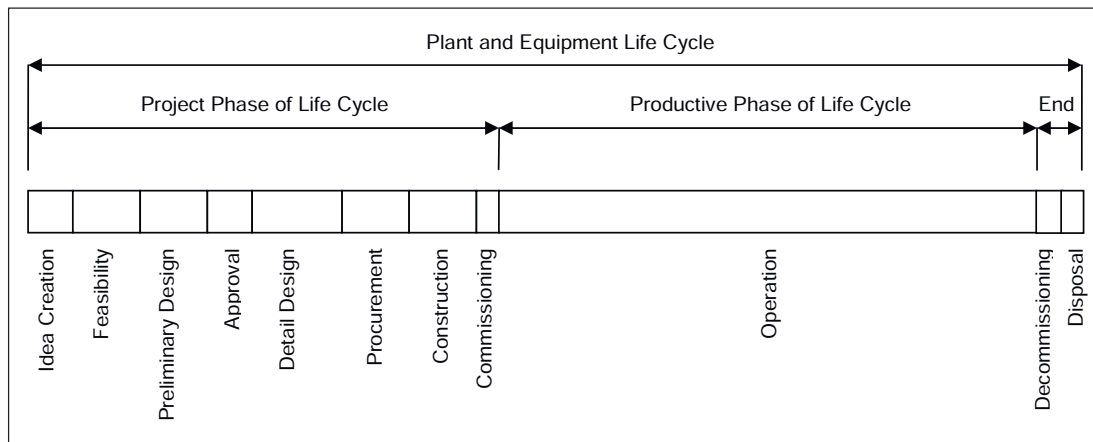


Figure 1.13 – The Life Cycle of an Industrial Facility involves Multitudes of Series Process.

With the use of parallel-tested tasks human error is controllable to any level of risk. At every stage and in every activity, paralleling our tasks with proof-tests means that we can produce world-class work performance in all we do. High equipment reliability is a decision you make and then you put into place the necessary practices and methods to deliver it with certainty.

## 2. The Physics of Failure

There is no forgiveness in machines pushed and distorted beyond their design capability. Machines need to be cared-for. They must stay within their design stress limits. Their parts must work in the ways the designer expected. Figure 2.1 represents a distorted conveyor pulley shaft in overload condition. When this happens parts fail fast. They can no longer handle the stress they are under. The load is too great and they fail from ‘overload’, or the material-of-construction degrades as stress damage accumulates and they fail from ‘fatigue’. As soon as a machine part deforms outside of its stress tolerance it is on the way to premature failure. Plant, machinery and equipment can only be reliable if their parts are kept within the stress limits their atomic structures can handle. Once the stresses from operating conditions are beyond a part’s capability, it is on the way to an unwanted breakdown.



*Figure 2.1 – Machine Distortion Overloads Parts.*

Retired Professor of Maintenance and Reliability, David Sherwin, tells a 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.

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 Figure 2.2 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 of a failure event and that is why the curves are known as probability density functions of ‘probability vs. stress/strength’. They reflect the natural spread and variation in material properties.

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 of the part under varying and combined 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 somehow 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.

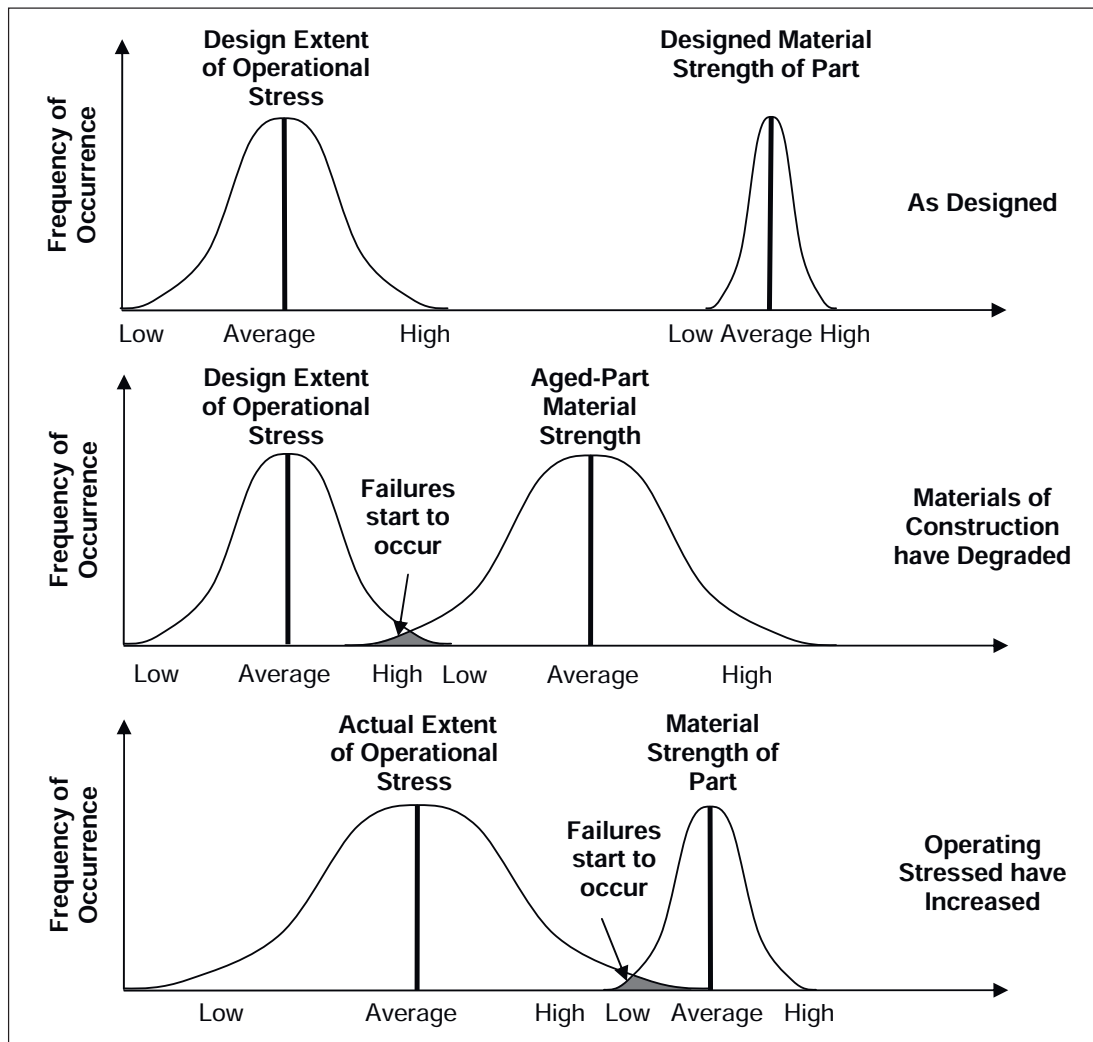


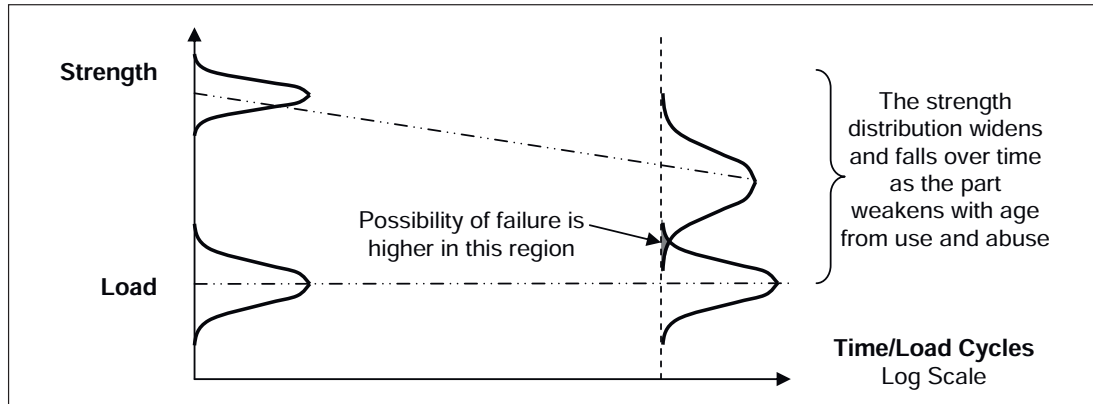
Figure 2.2 – Parts Fail When the Stress in Parts is Greater than the Strength of Parts.

The equipment designer's role is to select material for a part with adequate strength for the expected stresses. The top curves of Figure 2.2 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. 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. Some 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 by the middle curves of Figure 2.2, 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 bottom curves represent the situation where operating stresses rise and overloads are imposed on aging parts. The range of operating stresses has grown. In some situations they are now so large that they exceed the remaining material strength of some parts and those parts fail.

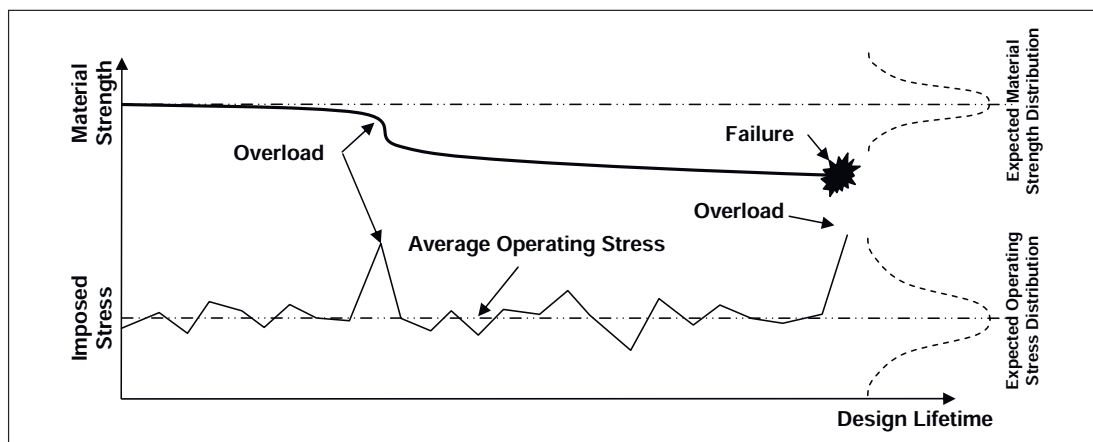
Many materials degrade with time, either from suffering stressful conditions, or from the accumulated fatigue of fluctuating stresses. Figure 2.3 shows what happens to material strength

through usage and abuse over time. The parts weaken and are no longer able to carry the original loads and stresses. As they fatigue the chance that some parts will encounter stresses above their remaining capacity to sustain them increases. Some of those parts eventually fail because a fateful load occurs that they cannot take.



*Figure 2.3 – Time Dependent Load and Strength Variation as Stress Damage Accumulates.*

Figure 2.4 shows how 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. Figure 2.4 also 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. 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 stressful situations overlapping.



*Figure 2.4 – Effects of Overload Stresses on the Failure of Parts.*

Products and parts fail if and when external stresses overload material strength. Products and parts also fail if and when material strength is decreased excessively by fatigue. The study of the mechanisms and processes of failure in parts and machines is known as Physics of Failure (PoF).

Figure 2.5 shows the best-practice process now adopted in designing equipment. It recognises the influences and effects of the Physics of Failure on parts<sup>8</sup>. 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.

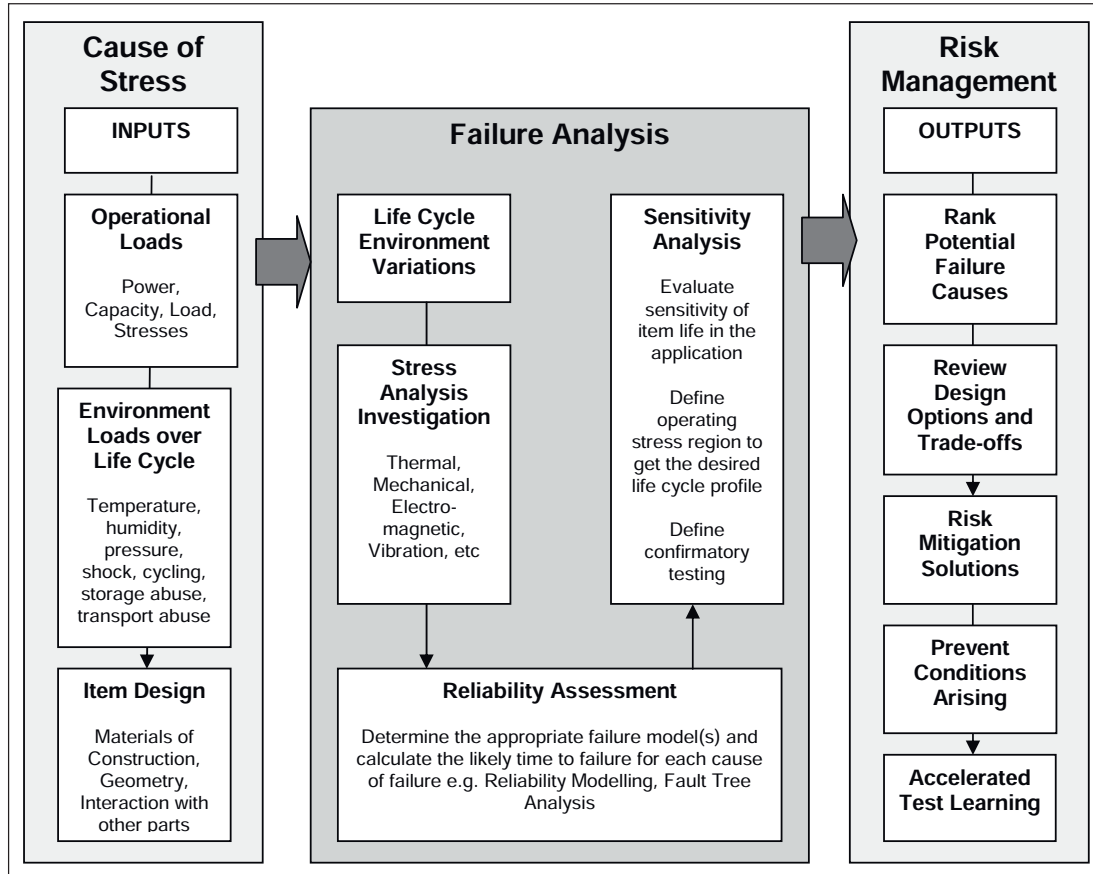


Figure 2.5 – Physics of Failure Approach to Reliability Improvement.

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 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 be twisted out-of-shape.

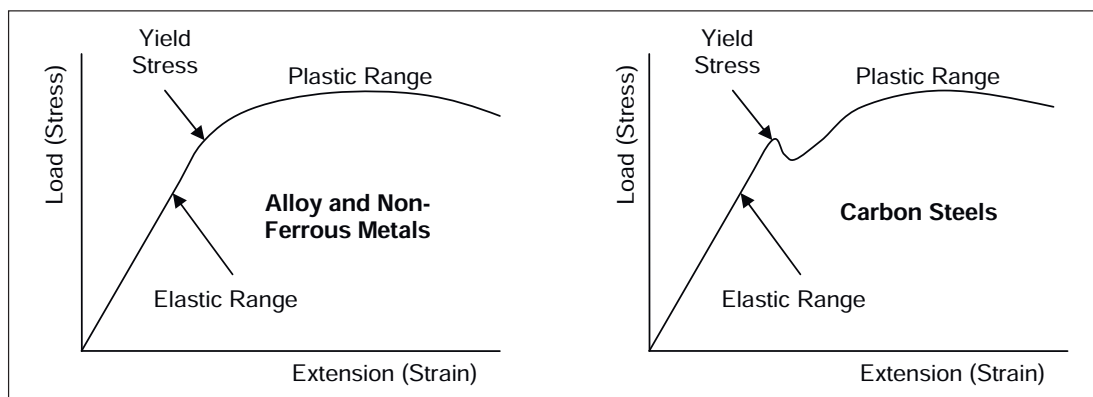
<sup>8</sup> Pecht, Michael., 'Why the traditional reliability prediction models do not work – is there an alternative?', CALCE Electronic Product and Systems Center of the University of Maryland, College Park, MD, 20742, USA.

## Limits of Material Strength

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<sup>9</sup>. 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<sup>10</sup>. Once the material of construction is damaged, even normal operating loads may be enough to extend the damage to the point of failure.

## Stress verses Life Cycle Curves

Have you ever bent a metal wire back and forth until it breaks from the working? If you have, then you performed a stress life-cycle test. A wire bent 90 degrees one way and then back 90 degrees the other way does not last long. Each bend produces an overstress. Eventually the overstressing accumulates as damage to the atomic microstructure and the wire fatigues and fails. The same effect happens to the electronic, electrical and mechanical parts in a machine put under excessive operational and environmental stress. Apply force to an object and it deforms. Its atomic structure is strained. The more the force applied; the more the deformation (strain). Figure 2.6 shows this relationship, known as Hooke's Law, for two types of metals. It indicates that metals have an elastic region where load and strain are proportional (the straight line on the graph). In this region the metal acts like a spring. Remove the load and the deformation (strain) reduces and it returns to its original shape. If instead the load increases, the strain (deformation) rises to a point the metal can no longer sustain the load and it yields like plasticine. The yielding can be gradual, as in the left-hand plot of Figure 2.6, or it can be sudden, as in the right-hand plot.



*Figure 2.6 – When Metals and Materials Reach Load Limits They Deform.*

There has been a great deal of fatigue load testing done with many materials. These tests produce graphs of tensile strength versus number of cycles to failure. They help us to understand how much load a material can repeatedly take and still survive. Figure 2.7 is an example of wrought (worked) steel commonly used in many industries. Under loads of 90% its maximum yield strength it will

<sup>9</sup> Gordon, J. E., *The New Science of Strong Materials or Why You Don't Fall Through the Floor*, Penguin Books, Second Edition, 1976.

<sup>10</sup> Juvinall, R. C., *Engineering Considerations of Stress, Strain and Strength*, McGraw-Hill, 1967.



last 2,000 cycles. Loads at 60% of maximum yield get 200,000 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.

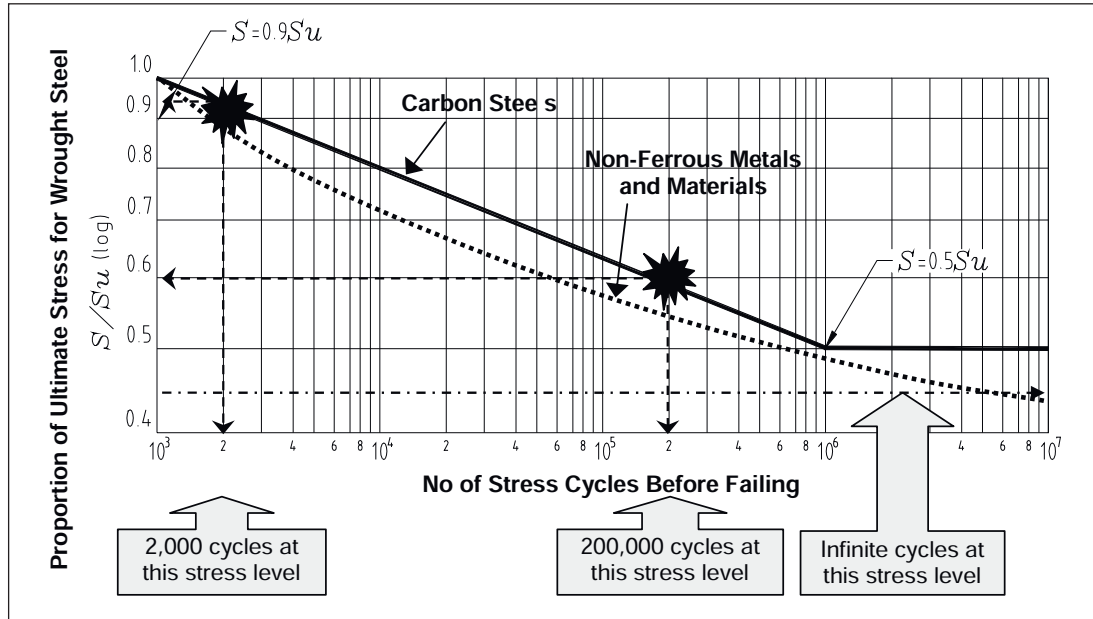


Figure 2.7 – Repeated Over-Stressing Causes Fatigue and Failure.

Metal fatigue depends on the number of stress cycles undergone by a part and the level of stress imposed in each cycle. Studies have shown that infinite life for a steel part is possible if the local stresses in the part are below well-defined limits. Fatigue failures increase if parts have stress raising contours or if stress raisers such as notches, holes and keyways are present in the part. There is also a relationship between a metal's ultimate tensile strength (highest point on the stress – strain curve of Figure 2.6) and hardness and its ability to handle fatigue loads. The higher the tensile strength and hardness the more likely it will fatigue if it is subject to high fluctuating loads.

We know that overstressed parts fail. The imposed overstress comes from external incidents where an action is done to overload the part. 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. Figure 2.8 shows how each overload steals a little operating lifetime.

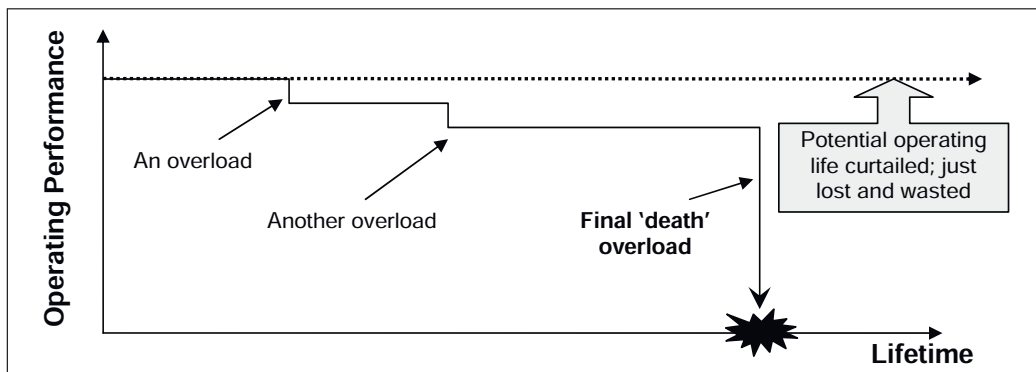


Figure 2.8 – The Stress-Driven Failure Degradation Sequence.



## Degradation Cycle

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 attack the part, for example from corrosion or erosion, the two factors – overload and weakening – act together to compound the rate of failure.

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 Figure 2.9. 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.

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.

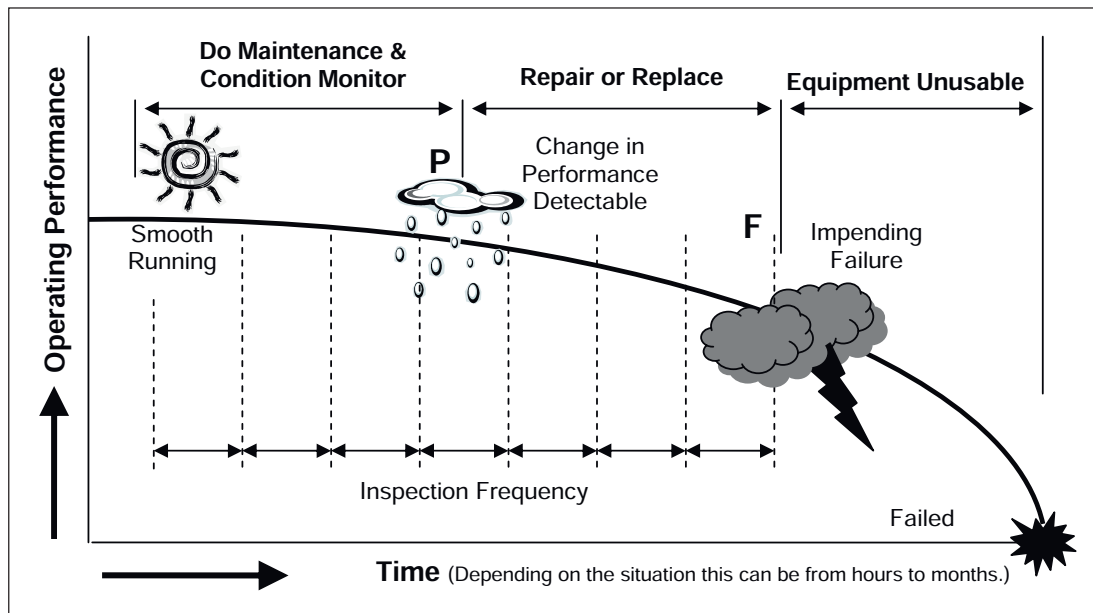


Figure 2.9 – The Fatigue-Driven Failure Degradation Sequence.

The point at which degradation is first possible to detect is the potential failure point<sup>11</sup>, 'P', in Figure 2.9. The point at which failure has progressed beyond salvage and the equipment performance is critically affected is the functional failure point, 'F'. We must condition monitor frequently enough to detect the onset of failure so we have time to address the failure before it happens. The condition monitoring can be as simple as regular 'feel and listen' observations of parts and equipment performance by the operator, through to complex continuous on-line monitoring with instrumentation using computer-controlled diagnostic and prognostic programs.

<sup>11</sup> Moubray, J., 'Reliability Centred Maintenance', Butterworth Heinemann, 1991.

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.

Overloads do not happen by themselves; someone put the excess loads on the part. Parts fail from ignorance, human error or unpredictable 'acts of God'. All but 'acts of God' are controllable by proper procedures and practices. And even the consequences of 'acts of God' can be mitigated with proper preparation and training. We must prevent and control the circumstantial factors that cause both fatigue and stress. From the start of a part's life as a drawing, to the day it is decommissioned and scrapped, its well-being and health depends entirely on how it is treated by people during its design, manufacture and operation. If you don't want machines to stop, keep the operating stresses on their parts low. This requires developing engineering, operating and maintenance procedures to prevent overloads, and then training engineers, operators and maintainers to follow the procedures with great certainty.

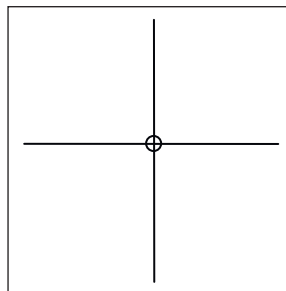
### 3. Variability in Outcomes

Probability, likelihood, chance: the more we learn about them, the more we realise how much they impact our lives, our businesses and our machines<sup>12</sup>. All around us things happen. People make choices and act. We only see the effects of those choices in the future. Often we can't differentiate one effect from another because past choices interact and react to make unknown and unknowable events happen. Operators, maintainers, manufacturers, engineers, managers, purchasing officers, suppliers, and many others, make choices all the time that impact the lives and reliability of our plant and equipment. With so many unknowns going on around us our machines, our businesses and our lives are seemingly at the mercy of luck and fortune.

These vagaries introduce variability: the cause of most of our operating and business problems. Variability is 'the range of possible outcomes'. A business with an aim of providing a product or service with consistent specifications does not want its processes behaving randomly; producing out-of-specification merchandise. Out-of-specification results are a waste of money, time and effort. Large amounts of a modern organisation's resources are devoted to controlling variability within their business and operating processes. The people involved in this duty carry the name Manager, Supervisor, Superintendent, (or the like) within their position title. Their role is to ensure that outputs are within prescribed limits. Anything outside those limits is urgently controlled. A business process with high variability means outcomes range from good, to mediocre, to disastrous. Things are uncontrolled; volatile. This volatility is the exact opposite of what is required in business. It is much more profitable to get the right result every time.

#### Observing Variability

There is a simple tabletop game to play that helps you understand why variability is a problem. It is a great introduction to controlling variability of processes. In Figure 3.1, two lines cross at 90° with a 2mm diameter circle drawn at their intersection. Sit at a table and drop a pen by hand into the circle from a height of around 300 mm (one foot). A hit within the circle is the 'process' outcome you require. Repeat the targeting and drop process at least thirty times. After each drop measure the Cartesian position of the new mark to an accuracy of half a millimetre. Record the horizontal distance from the vertical line (the 'x' distance) and the vertical distance from the horizontal line (the 'y' distance) in a table like that of Table 3.1.



*Figure 3.1 – The Cross-Hair Game.*

Observe the average and spread, of the 'X' and 'Y' results. In Table 3.1, no hits are within the two millimetre circle; some are on the edge, or near, but most are well away. Even though great effort was made to control the 'process', the results are across a wide band of outcomes. The process outcomes spread across a range of results; there is no repeatability. That is variability.

<sup>12</sup> Mlodinow, Leonard, 'The Drunkard's Walk – How Randomness Rules Our Lives', Allen Lane (Penguin Books), 2008.

This same problem is common in business and operations processes. It causes serious waste and loss for a business when its processes produce results that are not consistently within required boundaries.

*Table 3.1 – Record of Cross Hair Game Hits.*

Hit No	Distance X	Distance Y	Hit No	Distance X	Distance Y	Hit No	Distance X	Distance Y
1	8.5	16	11	1.5	5	21	1.5	5.5
2	7	9	12	1.5	20	22	3	3
3	4	16	13	3.5	3.5	23	3.5	0
4	3.5	2.5	14	2.5	12	24	2.5	6
5	5	24.5	15	3	24.5	25	0.5	2
6	5	16	16	4.5	6	26	1	2
7	7	10.5	17	4	12.5	27	3.5	10.5
8	5.5	9.5	18	5.5	5	28	1	9
9	2	3.5	19	1	9	29	4	14
10	3	2	20	6	4.5	30	0.5	3.5
			<b>Average</b>	X = 3.48	Y = 8.90			
			<b>Spread</b>	0.5 - 8.5	0 - 24.5			

If the aim of the game is to have every pen-drop fall inside the 2mm circle, then we have a very poor process for doing that. To get better results requires changing the process. To win the game requires inventing a different process that successfully puts the pen inside the 2mm circle every time. The results in Table 3.2 were from a process where the pen was dropped after aiming at the circle from above, much like using targeting sights to drop a bomb from an aeroplane.

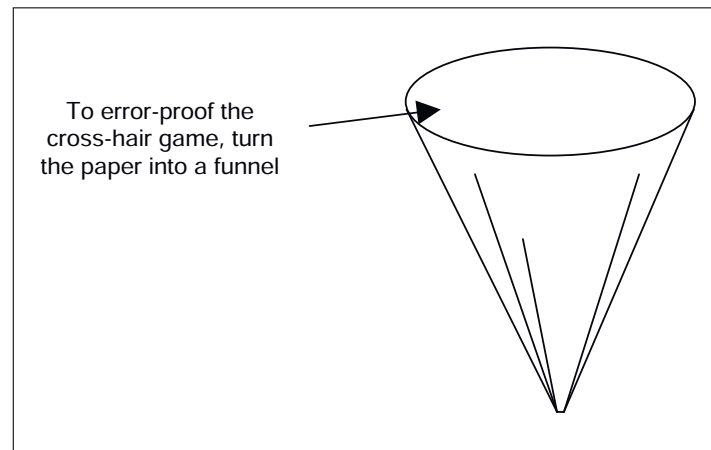
*Table 3.2 – Record of Cross Hair Game Hits Using a Sighting Process.*

Hit No	Distance X	Distance Y	Hit No	Distance X	Distance Y	Hit No	Distance X	Distance Y
1	8	10	11	5.5	6	21	3.5	0
2	5	6	12	2	4.5	22	2	5
3	4	3.5	13	0	1	23	0.5	1
4	3	4	14	5	2	24	6.5	0
5	2.5	1	15	4	7	25	3.5	3
6	2	0.5	16	3	1	26	0	8.5
7	13.5	7.5	17	3.5	5	27	6	1.5
8	10.5	9.5	18	4	0	28	0	4
9	1.5	7	19	4	1	29	2	1.5
10	7.5	6.5	20	2	2.2	30	0	6.5
			<b>Average</b>	3.82	3.87			
			<b>Spread</b>	0 - 10.5	0 - 10			

The results of the second attempt to play the cross-hair game using a modified process are better; the 'X' and 'Y' values are virtually the same. The averages indicate that the hits were closer to the intersection than in the first process used. There is less spread. But the second process is still not suitable for meeting the requirements. It is very unlikely that any process using human hands to drop a pen within a 2 mm circle from a height of 300mm has sufficiently accurate control. Using human hands cannot meet the required accuracy. You could tell the person dropping the pen to 'try harder', to 'improve the quality of their efforts', but you would be a fool, because it is the process that cannot do what is required; not the person. To get the pen consistently within the circle requires the creation of a better process that removes the variability caused by the human hand.

There have been a number of process changes proposed by past players. These include a long, tapered funnel to guide the pen onto the target; a tube in which the pen slides; a vee-shaped slide to direct the pen into the circle; a guide rod with the pen fixed in a slider that moves up and down the rod, and a robot with a steady manipulator to drop the pen. As good as these solutions are they involve human interaction in locating guides and maintaining equipment. When people are involved in a process there will be mistakes made at some point. The 'human factor' issues cause variation and inconsistency. But if the solution were error-proofed, it would not matter where the pen drops, it always ends-up within the circle.

There is one error-proof answer known to the Author. It requires that you use the paper in a different way. My thanks and respect goes to the tradesman boilermaker that suggested it. Figure 3.2 is his solution: make the paper into a funnel with the 2mm circle at the bottom. No matter where the pen is dropped it always goes in the circle. This error-proofed solution turns a very difficult problem into one that is always perfectly done. Human error has no effect on the outcome.



*Figure 3.2 – Error-Proofing the Cross-hair Game.*

An answer jokingly suggested from time to time is to open the circle up to 50mm diameter and then everything will be on target. The suggestion totally defeats the purpose of having a process that delivers accurate results. Unfortunately many businesses unwittingly select it as the solution to their problems. They chose to 'widen the target' and accept any result, good, mediocre or disastrous, rather than set high quality standards and improve their processes to meet them. A business that does not pursue excellence in their activities will not last <sup>13</sup>.

Examples of processes with inherent high variability are those that at some point:

- require decisions
- require choices
- are done without exacting training
- have no standards
- have inadequate procedures
- lack correct information
- are ill-defined
- are based on opinion
- involve emotion
- have multiple ways to be done
- are not measured
- have high rates of equipment failure
- involve interpretation of data
- alter settings based on historic results

<sup>13</sup> Denove, Chris., Power, James D. IV., 'Satisfaction – How Every Great Company Listens to the Voice of the Customer', Penguin, 2006.

In these situations randomness and uncertainty abound. This is particularly the case in sales and marketing, finance, human resources, administration, engineering, design, customer service, production, manufacturing, procurement, dispatch, after-sales service and maintenance. In other words, it is every process in a business.

The late quality guru, advised graphing the process variables and the process outputs over time on a run-chart to identify uncertainty and variability <sup>14</sup>. When the run-charts are used together they locate the times and cause of poor results. If you want feedback control over a process then track the process variables – those factors that influence the result – so they are observable if they change. If the change is bad you react and correct it before it does too much damage. If you want pre-emptive control of a process then trend the variables of the process inputs before they enter the process. By ensuring the inputs into a process are correct you can be more certain the process they feed will behave right.

If you only want to know how well a process performed, then monitor its final output; the product from the process. Unfortunately monitoring the final output puts you in the position of asking, “What happened?” when something goes wrong. Just like the company in Example E3.1, who had no idea what had changed to cause a spate of raw material stock-outs. But by tracing the replenishment process on two run-charts it was possible to highlight process fluctuations and identify their underlying causes.

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### **Example E3.1: Inventory Replenishment Mayhem**

The stock replenishment process involved the ocean shipment of raw material from a manufacturer to the company. For some months prior the investigation the company had been running out of stock across a range of products. The impact on the company’s business was the inability to supply products on-time to their clients because their warehouse replenishment process could not maintain adequate raw material stocks. They were using-up safety stock and not getting resupply quickly enough to meet clients’ orders. Annoyed clients told them of the problems being caused in strongly worded correspondence and angry telephone calls. The company did not know why they had the stock-outs.

The investigation began by collecting data on products stocked-out over the previous two years. Table E3.1.1 shows the frequency plot spreadsheet of products that had suffered stock-outs in the prior two years. The company was suffering increased numbers of stock-outs over an increasing number of products. The frequency plot proved and confirmed the seriousness of the situation.

The next step was to find what was causing the lack of supply. It was necessary to look at the history of deliveries from the manufacturer. Historical records of delivery dates are in Figure E3.1.1, which is a run chart graph of the delivery dates. It shows a great deal of variability in the deliveries over the most recent months. Lately they were up to two weeks overdue, when they should have been arriving weekly.

Figure E3.1.2 is a graph of the numbers of sea containers in each delivery. It shows variability in the amount of product sent on each shipment. Instead of having their normal deliveries of ten to eleven sea containers, the company was receiving varied shipments from four to twenty-seven containers.

Further inquiries found that the regular national shipping line used for raw material deliveries had one of its two ships in for a two-month maintenance outage. Where once there was regular weekly shipment, now the only ship left on the run was fortnightly. To get product to

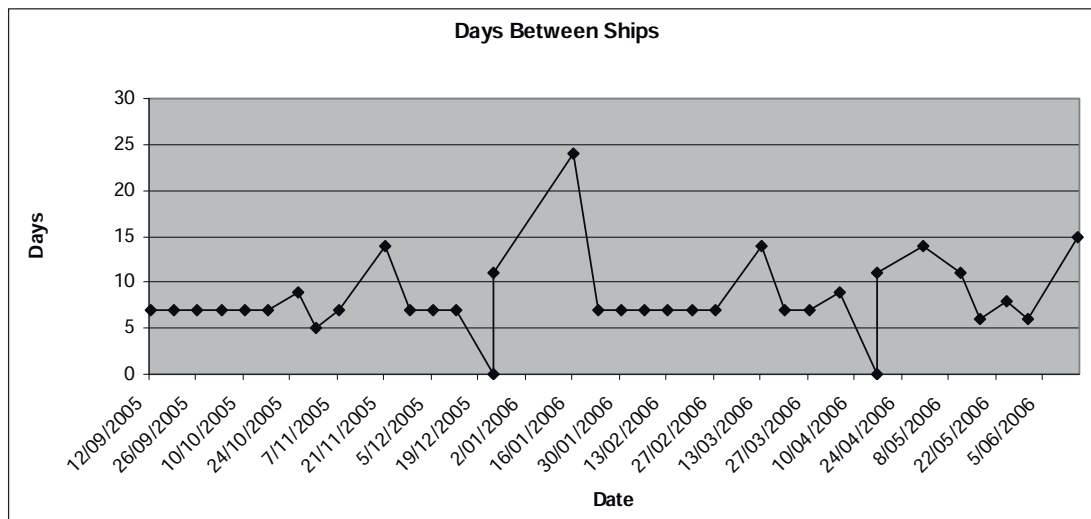
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<sup>14</sup> Deming, W. Edwards, ‘Out of the Crisis’, Page 49, MIT Press, London, England, 2000 edition.

the customer during the maintenance outage the manufacturer had started booking transport with international shipping companies. These ships had irregular departure schedules and only took numbers of sea containers they needed to fill the empty bays left after meeting prior commitments. Sometime they took few containers and other times they took many. The consequence of the irregular departure of the international carriers with either small or large amounts of product was the stock-outs suffered by the company.

*Table E3.1.1 – Frequency Plot of Product Stock-Out.*

Item	Total	Jun	May	Apr	Mar	Feb	Jan	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan	Dec	Nov	Oct	Sep
T166	21	1	1	2	2	3	1	1				1	1		1		1	1		1	1	1	1
T129	14			2	1	2	1			1	1			1	1							1	
T209	13	1		2			1											1		2	2	1	2
T201	10	1	1	1		1	1		1										1	1			1
T281	10	2	1		2																1	2	
T126	9	1	1	1										1			1			1	1	1	
T169	8	1	2	1				1				1								1	1		
T241	5	1															2			1			
T321	4																					1	
T161	5			2									2	1									
T361	3			1														1					
160N	11	1			1	1	2	2	2	1	1							1					
120N	9	1	1	1		2											1			3			



*Figure E3.1.1 – Ship Departure Dates.*

The company suffered because of the irregular supply of raw materials from the manufacturer. The irregularity was due to the high variability of international ocean shipping, further complicated by the feast-or-famine quantities of product on each ship. Variability in the replenishment process had caused major disruption to the customer's business. In response to the temporary shipping problems, they increased their order size, which effectively raised their inventory levels in-transit until the repair and return of the regular national carrier's second ship to the weekly run. To prevent future stock-outs required monitoring the shipping arrangements of the manufacturer to check for delays in sea shipment, and if so a rail delivery could be booked instead.

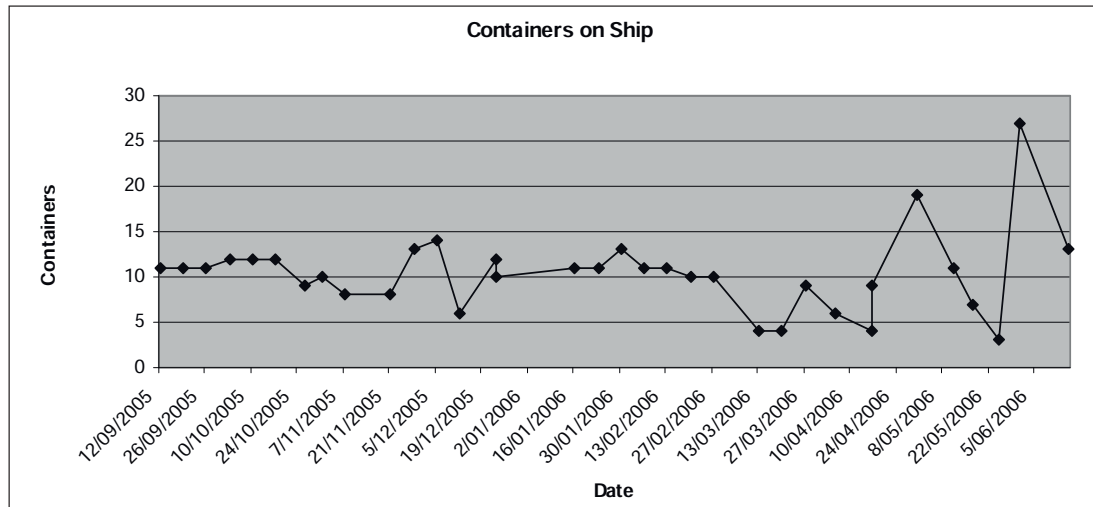


Figure E3.1.2 – Numbers of Containers on Each Ship.

The disruption of regular delivery to the company in Example E3.1 was the result of a ‘special cause’ event – the ship repairs. A ‘special cause’ event is an extraordinary occurrence in a process not attributable to the process. Had there been no ship repairs the deliveries each week would have been normal. The ship repair was outside of the control of the replenishment process but it impacted badly on it.

Fluctuation that is due to the natural variability of a process is called ‘common cause’ variation. The cross hair game is an example of the effects of common cause variation. Where the pen lands depends on the behaviour of the process variables affecting the drop, such as steadiness of hand, accuracy over target, evenness of release, etc. A  $\pm 25\text{mm}$  spread of hit locations is normal for the cross hair game. To have a pen fall into a 2mm circle when using a process with  $\pm 25\text{mm}$  variation has all to do with luck rather than with skill. Dropping a pen by human hand from a height of 300mm and expecting it always hit inside a 2mm circle is impossible, the common cause variability of that process is too great for the accuracy required. To always hit inside the circle needs a process without the element of luck, not an increase in the skills of the person doing the job.

An example of a classic misunderstanding of variability that makes equipment breakdown is the tightening of fasteners. This misunderstanding is the root cause of many flange leaks, fastener looseness and machine vibration problems. Figure 3.3 shows the variation in the typical methods use to tighten fasteners<sup>15</sup>. The method that produces the greatest variation, ranging  $\pm 35\%$ , is ‘Feel – Operator Judgement’, where muscle tension is used to gauge fastener extension. Even using a torque wrench has a variation of  $\pm 25\%$ , unless special practices are followed that can reduce it to  $\pm 15\%$ .

It is impossible to guarantee accuracy when tightening fasteners by muscular feel. Using a process that ranges  $\pm 35\%$  to get within  $\pm 10\%$  of a required value is like playing the cross-hair game – it requires a great deal of luck. Those companies that approve the use of operator judgement when tensioning fasteners must also accept that there will many cases of loose fasteners and broken fasteners. It cannot be otherwise because processes that use torque to tension fasteners have a high amount of inherent variation. It would be a very foolish manager or engineer who demanded that their people stop fastened joint failures, but only allowed them to use operator feel, or tension wrenches, to control the accuracy of their work. Such

<sup>15</sup> ‘Fastener Handbook – Bolt Products’, Page 48, Ajax Fasteners, Victoria, Australia, 1999 edition.



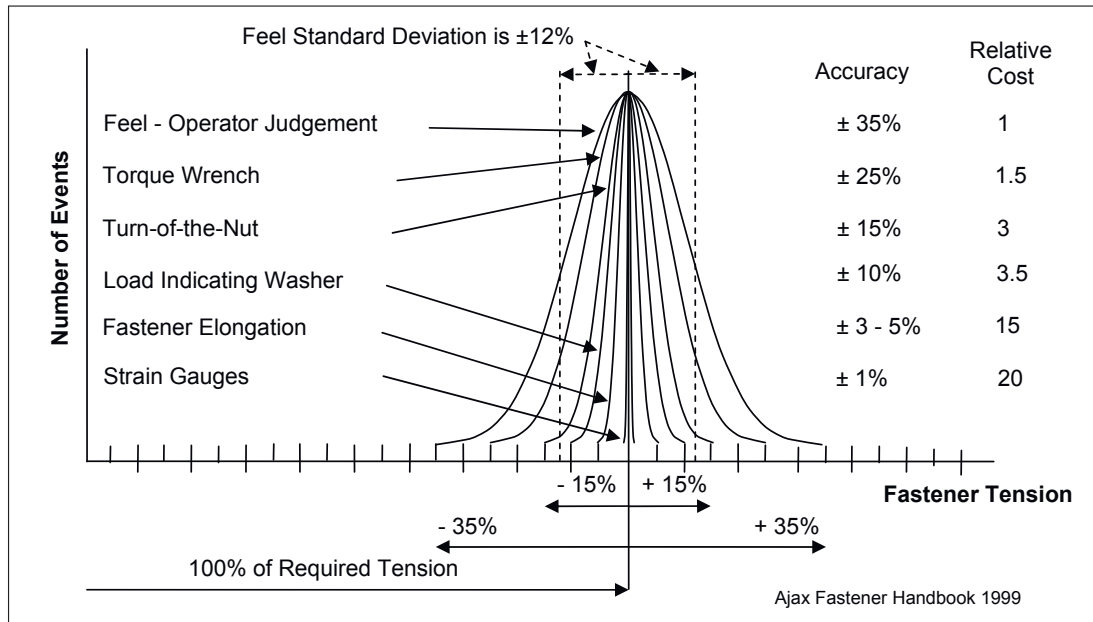


Figure 3.3 – Variability in Methods of Providing the Correct Torque for Fasteners.

a manager or engineer would come to believe that they have poorly skilled and error-prone people working for them, when in reality it is the process which they specified and approved that is causing the failures. They have totally misunderstood that it is the process being used that is not accurate enough to ensure correct fastener tension, not the people.

Joint failure is inherent in the muscular-feel process. Torque is a poor means for ensuring proper fastener tension. To stop fasteners failing needs a process that delivers a required shank extension. The fastening process must guarantee the necessary fastener stretch. Only after that management decision is made and followed through by purchasing the necessary technology, quality controlling the new method to limit variation, and training the workforce in the correct practice until competent, can the intended outcome always be expected. The use of operator feel when tensioning fasteners is a management decision that automatically leads to breakdowns. Any operation using people's muscles to control fastener tension has failure built into its design – it is the nature of the process. This is why W. Edwards Deming said his famous warning to managers, “Your business is perfectly designed to give you the results that you get.” Poor equipment reliability is the result of choosing to use business and engineering processes that have inherently wide variation. These processes are statistically incapable of delivering the required performance with certainty, and so equipment failure is a normal outcome of their use and must be regularly expected. Failure is designed into the process and it is mostly luck that keeps these companies in business.

The operating lives of roller bearings are another example where the effects of random chance and luck are not considered by managers and engineers when they select their maintenance strategies. The common maintenance practice of changing oil after it is dirty is a business process that designs failure into equipment. When management decide to replace lubricant only when it is dirty they have unwittingly agreed to let their equipment fail.

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<sup>16</sup> to 5 micron. Eighty percent of lubricant contamination is

<sup>16</sup> Jones, William R. Jr., Jansen, Mark J., ‘Lubrication for Space Applications’, NASA, 2005.

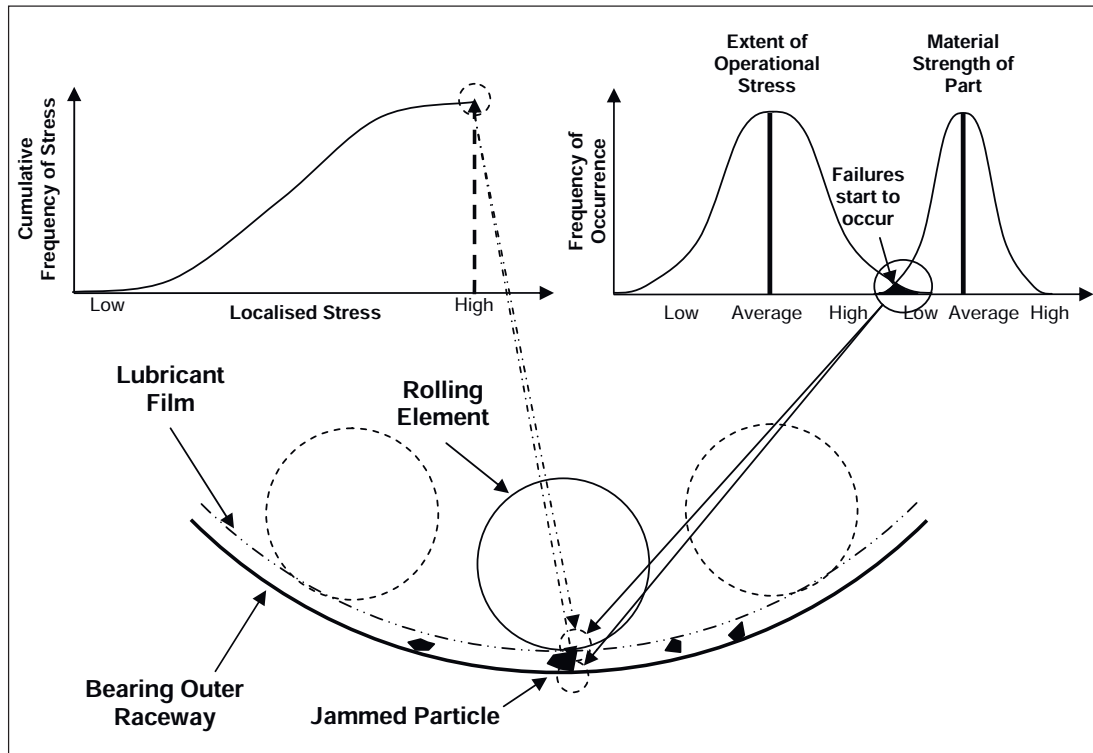


Figure 3.4 – Particle Contaminant Caught between Roller and Race Causes Overload Stresses.

of particles less than 5 micron size<sup>17</sup>. 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. The bottom diagram in Figure 3.4 shows a situation of particle contamination in the load zone of a bearing. 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. Depending on the size of stress developed, the surfaces may or may not be damaged by the particle. Low and average stresses are accommodated by the plastic deformation of the material-of-construction. However an exceptionally high stress punches into the atomic structure, generating surface and subsurface sub-microscopic cracks<sup>18</sup>. Once a crack is present 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 in a roller bearing when a light load supported on a jammed particle 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. 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 directly related to the processes selected to maintain and operate equipment.

<sup>17</sup> Bisset, Wayne, 'Management of Particulate Contamination in Lubrication Systems' Presentation, IMRt Lubrication and Condition Monitoring Forum, Melbourne, Australia, October 2008.

<sup>18</sup> FAG OEM und Handel AG, 'Rolling Bearing Damage – recognition of damage and bearing inspection', Publication WL82102/2EA/96/6/96.

*Table 3.1 – ISO 4406 Particle Count for Lubricant.*

Range Number	Number of Particles per Millilitre		Increase in Particle Count from 10 Range	Visual Colour
25	160,000	320,000	32,000	
24	80,000	160,000	16,000	Dark
23	40,000	80,000	8,000	
22	20,000	40,000	4,000	
21	10,000	20,000	2,000	Dirty
20	5,000	10,000	1,000	From drum
19	2,500	5,000	500	
18	1,300	2,500	250	
17	640	1,300	130	
16	320	640	64	Clear
15	160	320	32	
14	80	160	16	Clean
13	40	80	8	
12	20	40	4	
11	10	20	2	
10	5	10		

The amount of contamination allowed in lubricant directly impacts the likelihood of roller bearing failure <sup>19</sup>. Table 3.1 lists some ISO 4406 oil contamination range numbers <sup>20</sup>. Each number has twice the solid particles in a millilitre of lubricant (a volume equal to about 20 drops of distilled water) as the previous range. Lubricant with a range number 21 (dirty lubricant) has 125 times the number of particles in each millilitre than a lubricant with 14 (clean lubricant). It can be implied from Table 3.1 that the chance of failure from particle contamination is greater when the oil gets dirtier, because the availability of particles to be punched into load zone surfaces, or to block oil flow paths, or to jam sliding surfaces, rises.

When a roller bearing is in use the rolling element turns and the races stay comparatively still. The odds that a damaged area on a roller is repeatedly stressed is low because the roller moves to a different spot. Whereas a damaged area on the race remains exposed to all rolling elements that pass. This means the chance of bearing race damage rises with increasing oil contamination by wear particles. But surface failure is not certain until sufficient stress is present to cause cracks. As we saw above, the size and frequency of stress seen by a bearing depends on many random factors. You could have very clean lubricant, and though the odds are extremely small, you may be unlucky enough to jam the only solid particle in the neighbourhood between roller and race at the same time as a rotating misalignment force spike passes through it. We can be sure that as lubricant gets more contaminated the chance to damage the races increases. With each rolling element that arrives over a surface the growing number of wear particles provide ever increasing opportunity to be punched into the surface.

The risk of failure to a company's plant and equipment from wear particle oil contamination is the direct result of the management processes applied (or not applied) to decide how much contamination will be sanctioned in their oil. Companies mistakenly allow their gearboxes, drives, bearing housings and hydraulic system oil to get dirty and blacken from wear particles before they replace it. Often they wait for an oil analysis to indicate contamination is too high, or replace dirty oil on time-based preventive maintenance. Unfortunately, by the time lubricant becomes dark from particle contamination, the probability of jamming a particle between two contact surfaces has markedly increased and failure sites have probably already been initiated in bearings. To significantly reduce bearing failures, gear failures and sticking hydraulic valve problems, the ISO4406 particle count must be kept at clear levels or below, so

<sup>19</sup> SKF Ball Bearing Journal #242 – Contamination in lubrication systems for bearings in industrial gearboxes, 1993.

<sup>20</sup> ISO 4406 – 'Hydraulic Fluid Power – Fluids – Method for Coding the Level of Contamination by Solid Particles'.

the oil never has many contamination particles in it. Changing dark oil is far too late to greatly reduce the probability of failure. The oil must never be darkened by particle contamination in the first place if you want to reduce the influence of luck and chance on your lubricated and hydraulic equipment breakdowns.

The managers and engineers in these companies are fervent that they do the right maintenance practices and have excellent preventive maintenance processes in place. They are wrong of course, because the processes they use cannot deliver the results they want. There are many organisations trying to achieve impossible results using business, engineering and operating processes with ‘common cause’ variation that cannot reliably produce the performance needed – they are playing the cross-hair game in everything they do. Such businesses employ processes containing inherent volatility that naturally produce outcomes outside requirements. Trying to manage an organisation with systems and processes that produce highly variable results is an exercise in futility that will cause great waste, distress for all involved and emotional burn-out for its managers, engineers and supervisors.

### **Controlling Process Variation**

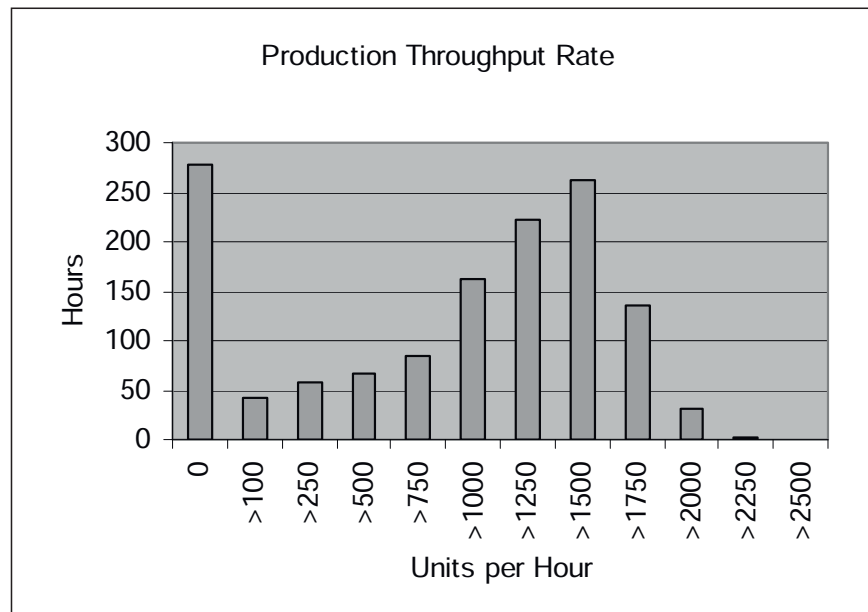
Controlling ‘common cause’ problems requires changes in how a process operates. In contrast, control of ‘special cause’ variability is by stopping the influence of the extraordinary event. Preventing the ship repair leading to late raw material deliveries in Example E3.1 was done by using other reliable modes of transport to replace the failed ship. As soon as on-time delivery by ship was not possible, the rail was booked. You address ‘special cause’ issues by stopping them from happening or by preventing them impacting your business. But ‘common cause’ issues are inherent in the process and their prevention requires changing the process.

It is the nature of every process to produce variation. The challenge for business and operations processes is two-fold. First it is to have only ‘natural’ variation and no ‘special cause’ variation. Second it is to select or develop processes with ‘natural’ variation well within the required performance. This allows the organisation to focus mainly on stopping ‘special cause’ problems, sure in the knowledge that the process itself is inherently stable and produces good product. When a business or operating process no longer performs within its normal limits, look first for a ‘special cause’ of the change. Only after all ‘special causes’ are eliminated can you be sure that just natural ‘common cause’ variation remains. If the ‘common cause’ variations are still too volatile, you have justification for improving or changing the process. By following that sequence you confirm if special cause variations are masking the natural process variability with effects that confuse the analysis. If a ‘special cause’ is mistaken for a ‘common cause’ you will make the wrong decisions to address the problem.

So far we have seen examples of variability in a game and variability in the supply chain of an organisation. Being able to get a ‘picture’ of the variability with run charts and tables brought a clearer appreciation of what was happening within the process. It allowed asking powerful, relevant questions that led to a more profound understanding of the situation’s causes and their resolution. There is great value gained when an organisation observes the variability of its business processes. Once a ‘picture’ is available of how a process behaves, companies can make focused efforts to control unacceptable variability. Example E3.2 is of a mining operation where the consensus was to invest a \$250,000,000 to expand production 50%, when in fact it may have been unnecessary if production variability had first been addressed.

**Example E3.2: The Hidden Factory**

Here is an example of the value of identifying causes of variability in a business. In this case, the production from an ore processing plant is trended on a simple bar graph. Figure E3.2.1 shows the graph of the hourly production rates of a 24 hour a day, 7 days a week milling operation during eight consecutive weeks. It provides a lot of valuable information about the operation's capacity, as well as a clear indication that the business is suffering wild fluctuations in its production throughput. Examination of the graph provides insights into the facility's dilemmas.



*Figure E3.2.1 – Production Rates.*

The eight weeks of production shown on the graph represent 1344 production hours. For 275 hours there was no production, so for 20% of possible production time the plant was standing still. The plant design capacity is 1500 units per hour. For 615 of the remaining hours it was running at under design rate. For 57% of the time that it was running it was delivering substantially less than designed production. The actual average production rate for the entire eight weeks is 1000 units per hour, which is two-thirds of design duty. This facility is suffering severe production problems and needs to investigate why it is not producing consistently at design capacity.

There is additional information in the graph. It is clear that for a significant number of hours the plant ran at above its design rate. There are two implications that can be speculated. One is that in trying to make-up for lost production the plant was overloaded, which then led to even more equipment failures and added downtime. The second is that the plant can be run at more than its design duty. Confirming each possibility would require an engineering design investigation. There is a good chance that with minimal engineering changes the plant could be run consistently at 2000 units per hour, which is a third greater than design capacity and twice current average production. The overstressing of parts would be a major concern at the increased production rate and would need to be addressed by a full design review. An operating risk analysis based on Physics of Failure consequences would be conducted and problems designed-out as part of increasing to a higher than original design production rate.

There are obvious questions to ask of a plant with this extent of variability in performance. Such as, 'what are causing the stoppages and below design throughput so often?', and, 'If the

plant can produce at higher rates by accidents of circumstance, then what could be consistently produced if those circumstances were deliberate?’ It would be sensible to identify both the causes of the disastrous production losses and solve them, while making the fortuitous accidents of the past intentional. The total ‘lost’ throughput represented by the stoppage time and slow running, plus the higher production rates available from re-engineered capacity, means that this operation has plenty of opportunity to deliver a large production increase without significant capital investment.

This company’s decision to spend \$250,000,000 on a major capital upgrade to boost production 50% may not have been necessary. By recovering the downtimes and low production rates, and re-engineering bottlenecks for higher throughput, the extra capacity was probably achievable with the old plant. It was only necessary to conduct root cause investigations on why the production losses occurred and solve them. The financial return on such an investment would be unbelievable. All these options became clear simply by measuring production variability.

To construct a graph like that in Figure E3.2.1 requires collecting the hourly production figures for a sufficiently long time to observe the full range of variability affecting the process. The figures will show a range of performance around a mean value. The extent of the spread below the mean will indicate if there are production problems hampering throughput. The range of spread above the mean will indicate if there is spare capacity available. If the spread is tight about the mean production rate then the operation is running well and it is performing as it should. But if, as in Figure E3.2.1, the spread is wide, then the plant has ‘hidden’ opportunities to improve its production performance and efficiencies.

When production throughput graphs have a wide spread of production rates, there is potential to increase plant capacity by removing the causes of operating losses with minor engineering upgrades, or removing the variability by adopting improved procedures and extensive training. Before you invest more capital to expand plant capacity, investigate the variability of current production, because there may already be a ‘hidden factory’ within your existing plant.

### Controlling Business Process Performance

The purpose of controlling variability is to provide certainty of performance. Once variability is identified it becomes necessary to make the decision to leave the situation alone and accept fluctuating outcomes, or to address the underlying problems causing the fluctuations. To

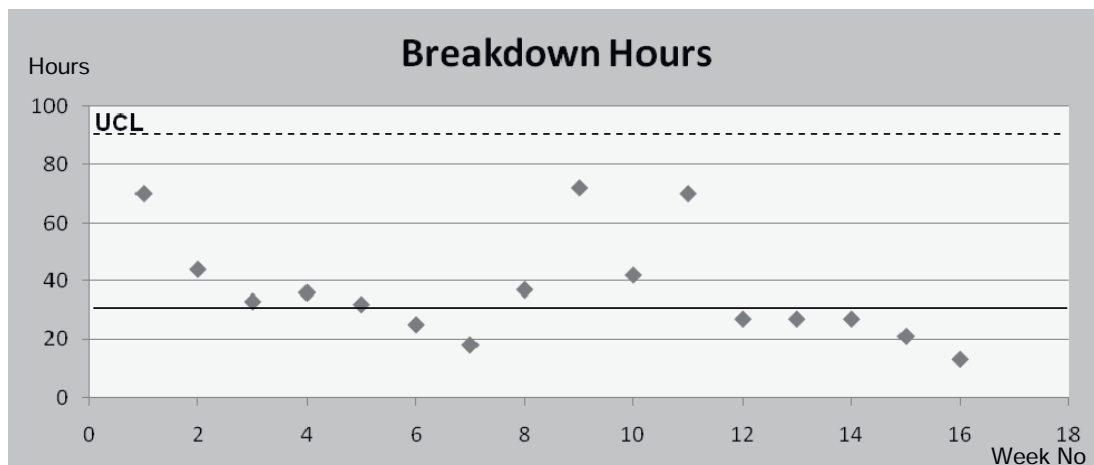


Figure 3.5 – Breakdown Hours per Week.



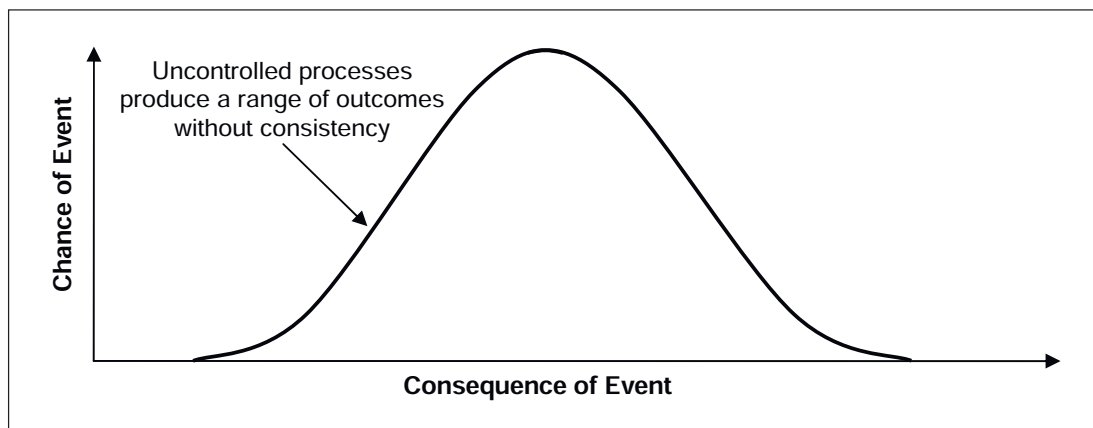
make improvements means finding the causes of the problems and then identifying ways to solve them.

Most industrial businesses make their equipment fail. You have already learnt how the misunderstanding of probability leads managers and engineers into using processes that cause equipment breakdowns. An analysis of a real business illustrates the effects of this all too common management problem. Figure 3.5 is a time series graph, or run chart, of a company's total breakdown hours per week for sixteen weeks. Important information about the company's way of operation is exposed by using basic statistical analysis. If the graph is representative of normal operation the time series can be taken as a sample of their typical business performance. 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. 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 has a statistically stable system for making their equipment breakdown. Breakdowns are one of its products.

Because the breakdown creation process is stable, the future generation of breakdowns is predictable and certain. If this time series is a true sample of normal operation, it can confidently be said that there will always be an average of 31 hours lost to breakdowns every week in this business. In the three weeks following the period represented in Figure 3.5 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 is to change to processes that prevent breakdowns.

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. Typically, business process variability fits a normal distribution curve, like in Figure 3.6<sup>21</sup>. When things are uncontrolled, the process produces a range of outputs that could be anywhere along the curve.

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. Figure 3.7 shows a minimum specification of performance for a process producing wide variation. The



*Figure 3.6 – Uncontrolled Processes Produce All Sorts of Results.*

<sup>21</sup> Many real-world processes are normally distributed, but distributions can also be skewed or multi-peaked.

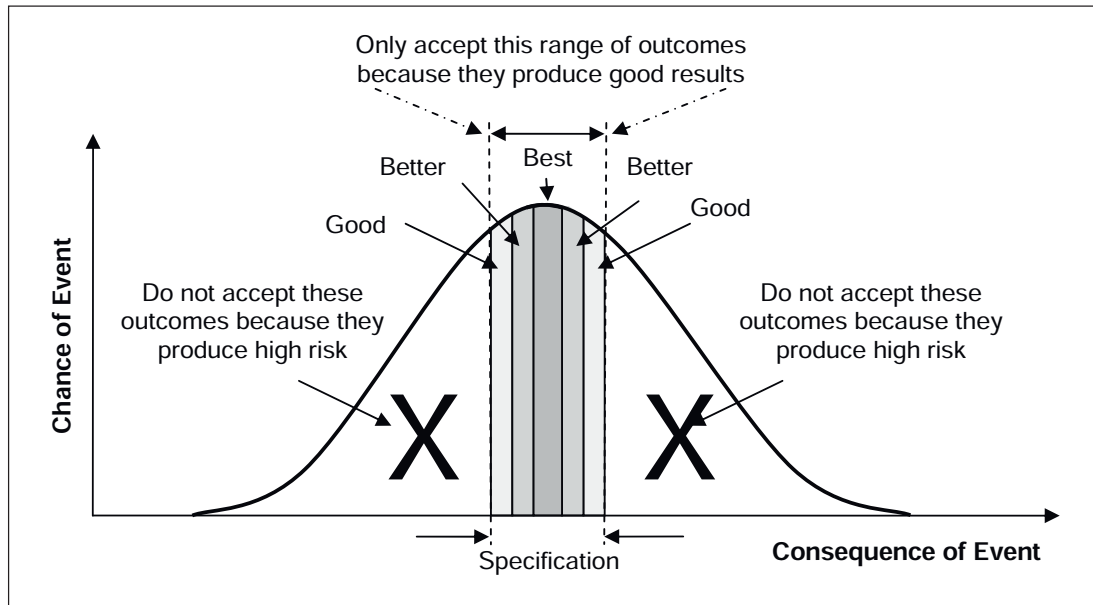


Figure 3.7 – Controlling the Chance of a Failure Event.

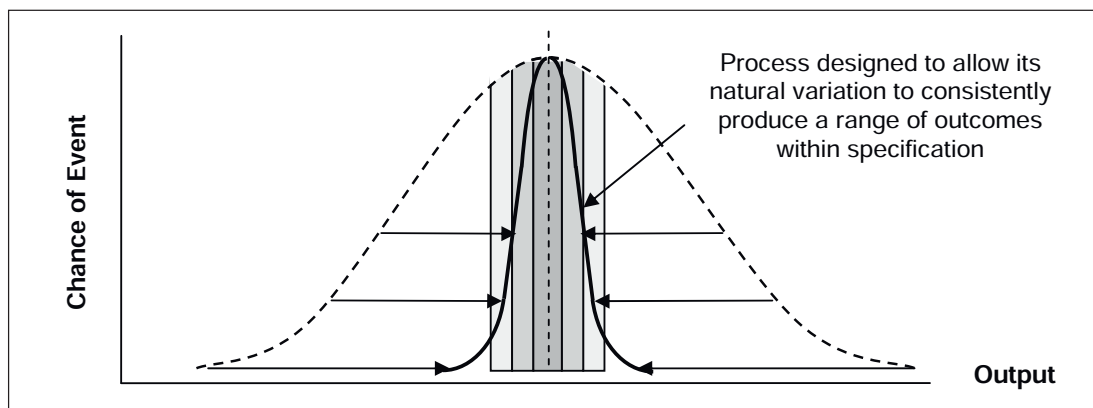


Figure 3.8 – The Effect of Removing Volatility from Business Processes.

acceptable range is further categorised by the precision control requirements of an Accuracy Controlled Enterprise, described in Chapter 14. Only those outcomes that meet or better the 'good' standard are acceptable. All the rest are defects and rejects.

By designing and installing better ways that remove the performance fluctuations the volatility in the process of Figure 3.7 can be reduced and stabilised. With volatility controlled the spread of results tighten around a consistent mean, as shown in Figure 3.8. Variation still exists but it is now within the desired limits. A process always producing repeatable outcomes within its control limits is in-control and capable. It becomes highly predictable and the results can be guaranteed.

## What Quality is

In his book 'Out of the Crisis', the late W. Edwards Deming advised that "quality must be built-in"<sup>22</sup>. Quality, Deming tells us, is installed at the source. It is designed in and made part

<sup>22</sup> Deming, W. Edwards, 'Out of the Crisis', Page 49, MIT Press, London, England, 2000 edition.



of the product or service; it is delivered by the business process design. Quality is a definite and 'hard' measure that can be clearly identified. Quality is quantified with engineering measures – the 'numbers' that when achieved, deliver customer satisfaction. In his view, a product or service has the right quality when the customer is so satisfied that they boast about it to the people they meet. The quality of the product or service is designed to ecstatically satisfy the customer. Word-of-mouth markets it.

The same certainty over quality, but applied to equipment parts, is necessary to deliver the outstanding equipment reliability and plant availability that produces world-class production performance. What is important to know about quality is that it must be measurable. Quality is not left up to people to interpret what they think it means – it is a management responsibility. It needs to be quantifiable – a length, a thickness, a resultant force or pressure, a colour, a smell, a viscosity, a period of time, a rate of change. You require a specific engineering value, even a collection of values, which defines a level of performance. Once the values are attained, the performance is certain and the required quality is achieved.

To make quality you need a target and a range of acceptance. It is impossible to know how to control quality until standards of allowable variability are set. Once a standard is specified it is then possible to measure if the processes used to achieve it are capable of meeting the standard. For the business reflected in Figure 3.5, the processes used can never deliver long periods of breakdown-free operation. They are not designed to produce a breakdown-free week. It is nearly impossible in this operation to expect more than a couple of days without breakdowns. This company needs to fundamentally change its business processes if they want to improve their equipment reliability. Their current reliability management does not work. In fact it causes breakdowns. Were the company to set a target average of (say) ten breakdown hours a week, it is clear from the graph that the current operation cannot achieve it, and a search for the methods and strategies to reach 10 hours breakdown per week would start. The great challenge for this company is to replace years of destructive practices in operations and maintenance with those processes and methods that produce high reliability. This change would start when they decide to create business processes that make more uptime.

It is necessary to change to a new game-plan when existing processes do not produce the required results. Figure 3.9 represents the strategic aim when changing processes to make them capable. Deming said that it is the responsibility of management to improve a process, no one else can do it.

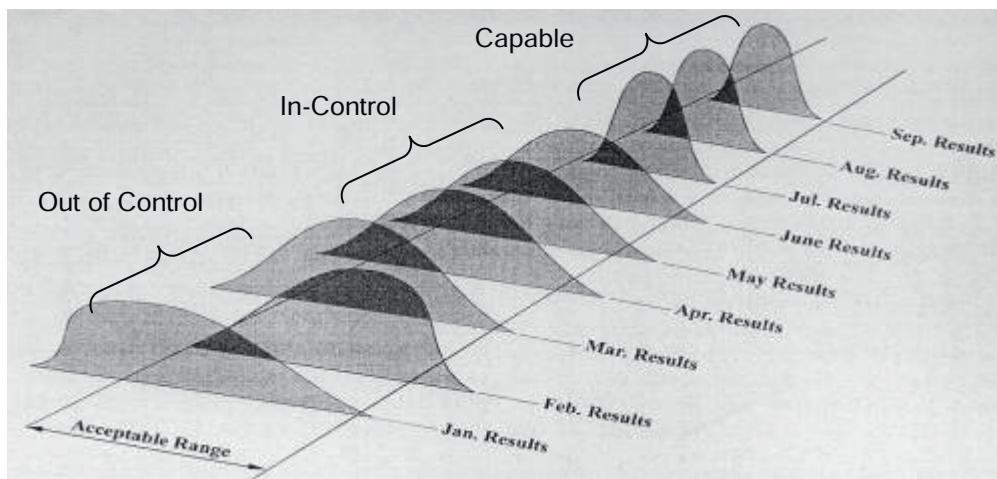


Figure 3.9 – Making a Process In-Control and Capable.

## Need for Setting Engineering and Maintenance Quality Control Standards

If shaft misalignment is present on equipment it does not mean that the machine will fail. Depending on the extent of misalignment, the operational abuse, clearance reduction from high temperatures, out-of-balance forces from unbalanced masses, and a myriad of other stress-raising possibilities, the size of the resulting stresses may still be lower than materials-of-construction strength. But it does mean that shaft misalignment increases the chances that loads will combine with others and add-up to produce a catastrophic failure. As more of these probabilistic stress scenarios become present in equipment, the chance of failure grows ever greater.

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 <sup>23</sup>. 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 <sup>24</sup>. The temperatures at which bearings operate change their internal clearances, which directly influence the likelihood of roller bearing failure <sup>25</sup>. 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 <sup>26</sup>. 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 banded 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.

## Making Things Visual

To control variability it is first necessary to observe it. This means monitoring the variables and their effects on process performance. A variable is any factor that influences the outcome

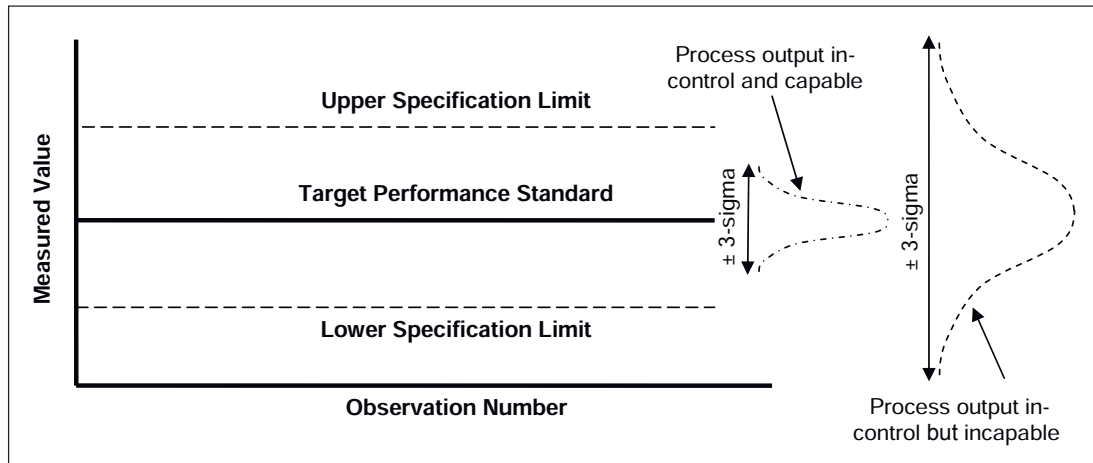
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<sup>23</sup> Piotrowski, John, Shaft Alignment Handbook, 3rd Edition, CRC Press, 2007.

<sup>24</sup> ISO 1940-1:2003 Mechanical vibration – Balance quality requirements for rotors in a constant (rigid) state – Part 1: Specification and verification of balance tolerances.

<sup>25</sup> FAG OEM und Handel AG, Rolling Bearing Damage – recognition of damage and bearing inspection, Publication WL82102/2EA/96/6/96.

<sup>26</sup> ISO 4406-1999 Hydraulic Fluid Power – Fluids – Method for Coding the Level of Contamination by Solid Particles.



*Figure 3.10 – A Basic Control Chart.*

of an action, process or decision. If the effects of a change in a variable are to be observed the change needs to be presented in ways recognisable by the human senses. Graphic and visual displays are preferred, but use of the other senses is also acceptable. Visual displays ‘picture’ the situation. Comparison tables, graphs, quality control charts and the like are typical. The simpler the means of tracking, the better: provided it truly reflects the situation and has the precision to provide control.

Figure 3.10 is an example of a Shewhart control chart recommended by Deming for showing the performance of a process. One was used in the example above of the business unwittingly breaking its own machinery. The run-chart made their story painfully clear. The process and variable performance is monitored by recording measurements from the actual operation and plotting them on the chart. Process performance is checked against the specification to see if the degree of control and capability required is present in the process. If the results are within tolerance and repeatable, the process is in control. When they show a trend toward loss of control, or are outside the tolerance limits, you have accurate information to make the decision to alter, change or stop the process or operation. There are numerous types of control charts and other statistical techniques used to monitor process and variable performance <sup>27</sup>.

### **Operator Involvement in Process Improvement**

Enlist your operators and maintainers in the continual observation for process variation. Give them low-cost diagnostic tools, such as those in Figure 3.11, and let them experience process variations and equipment condition variations for themselves. They will learn to identify changes from normal operation and recognise impending problems. Providing operators and maintainers with simple, hands-on diagnostic tools gives them the opportunity and responsibility to spot problems and to fix them before failure stops the operation. It hands ownership of plant and equipment operation and well-being to them – the people ideally placed to get the best from their equipment.

The most successful oil refineries in the world are those that employ the production operators to observe their plant and equipment and report back to maintenance any discrepancies they observe <sup>28</sup>.

<sup>27</sup> Gygi, Craig et al., ‘Six Sigma for Dummies’, Wiley Publishing, 2005.

<sup>28</sup> Block, H P., Hernu M., ‘Performance Benchmarking Update; expectations and reality’, Gulf Publishing Company, 2007.

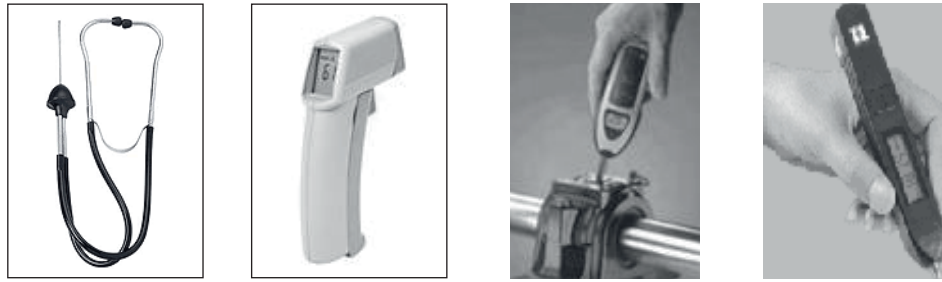


Figure 3.11 – Stethoscope Laser Thermometer Touch Thermometer Vibration Pen.

### Defect Creation, Defect Management, Defect Elimination Business Model

Variability crosses borders. It leaves the manufacturer and goes to the purchaser. Every product purchased, every service requested has within it the effects of the manufacturer's process variability. An item or service supplied should be within a range of acceptability specified by the customer, and delivered by the manufacturer or provider. The range must be easily achievable by the natural variation of the processes used. If a business has systems that produce a very narrow spread of results their products or service will have consistent performance. If instead they 'widened the target' and accept large process variations their customer will have problems. The two distribution curves in the control chart of Figure 3.10 show one business with processes in-control and capable of meeting the specification, while the other business will have many warranty claims.

Because variability exists in all processes, a range of outcomes are possible. The cross-hair game and the examples in this chapter highlight some of the bad effects and results process variability causes organisations. When variability becomes excessive you get defects and failures. A defect is a 'non-conformance to requirements or function'. It is a deficiency. It means bad quality went into service. Defects that escape correction lay hidden and may not become apparent until they cause a failure. A failure is 'an event or circumstance which prevents the accomplishment of an intended purpose'. A failure happens when a system or component is unable to perform its designed role. A failure is anytime a thing does not do its job. Figure 3.12 is a modified version of the DuPont Chemicals defect and failure model<sup>29</sup>. It highlights some of the many processes where failure causing defects and errors enter an operation.

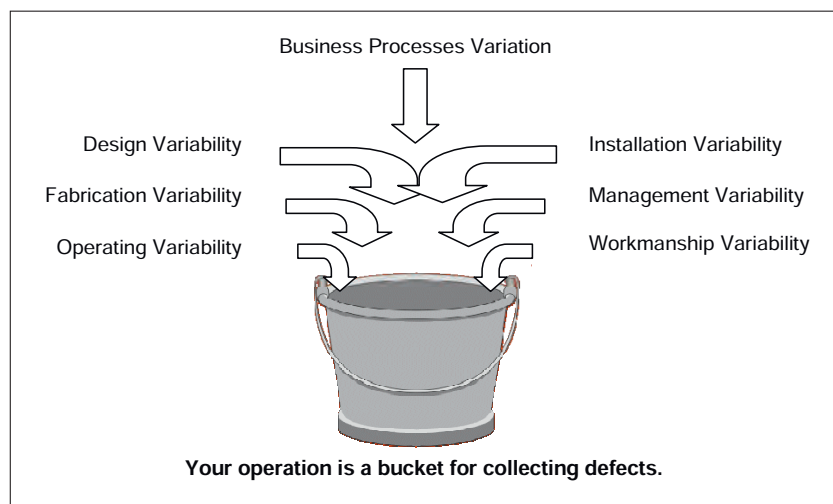
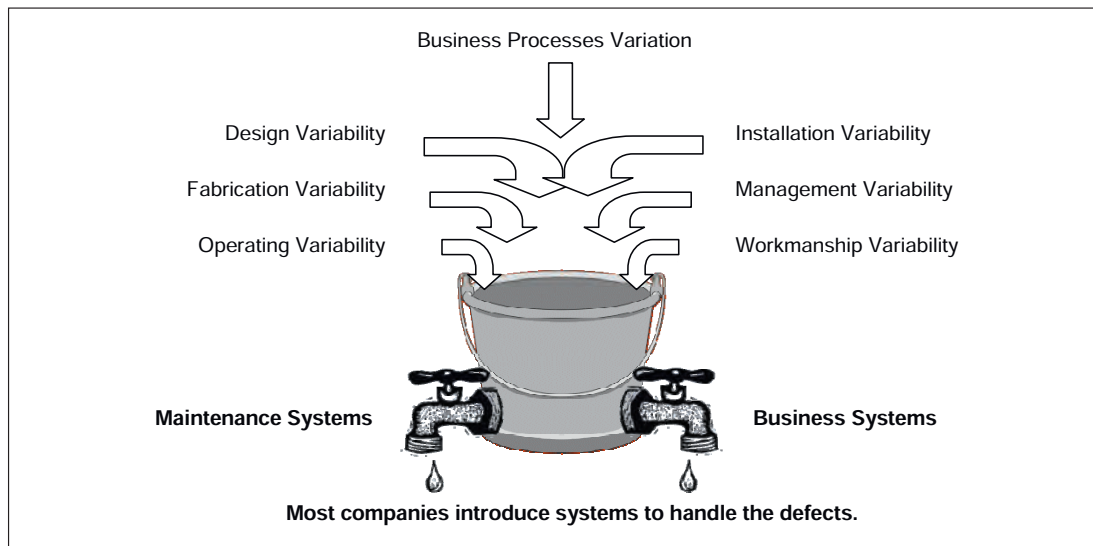
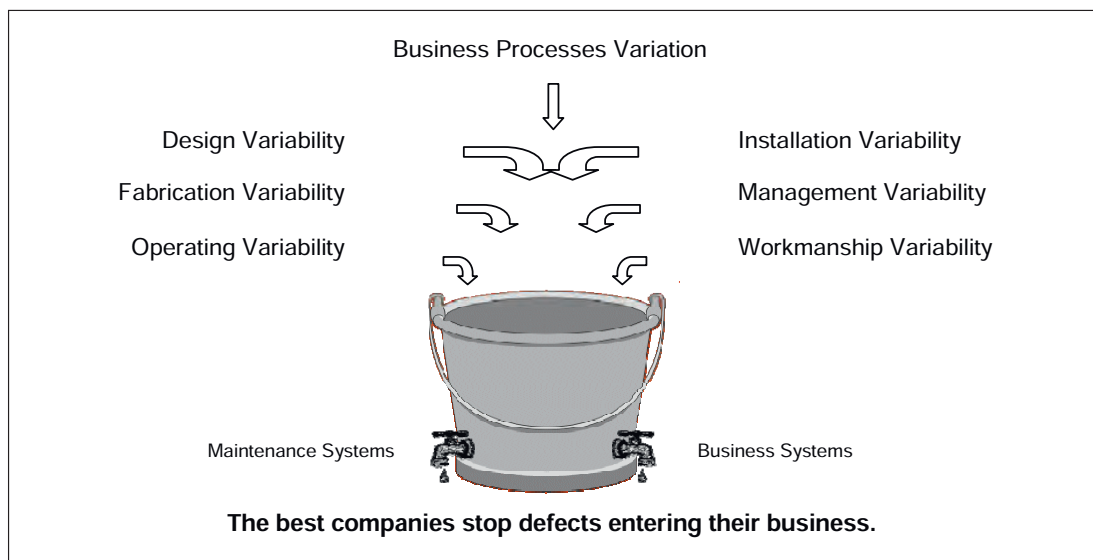


Figure 3.12 – Defect Creation.

<sup>29</sup> Ledet, Winston J., 'Engaging the Entire Organisation in Improving Reliability', The Manufacturing Game™, Atlanta, Georgia, USA.



*Figure 3.13 – Defect Management.*



*Figure 3.14 – Defect Elimination.*

Most businesses typically react as shown in Figure 3.13. They introduce maintenance and repair systems to manage the presence of failure. They accept defects as normal. Consequently they suffer production downtime and high maintenance costs as the effects of the introduced problems become failures.

Figure 3.14 shows the best strategy. It is to stop defects entering your business. Your quality improves, maintenance costs reduce and production uptime lifts. The defects that never occur allow equipment reliability, plant availability and productivity to rise because there are no failures. All the moneys not spent on failure-correction and repairs, and the extra income from throughput made in the production time recovered, are banked as profits.

Because every process in a business produces variable results, the more processes that there are the greater is the opportunity for defects and failures. Those organisations that try and do everything themselves have many processes to manage and control. Each process introduces its own variation. The final product will contain the full range of variability from each process used during its life cycle – design, supply chain, manufacture and assembly. Often companies



use external suppliers to provide parts and services in-place of using in-house produced commodities. But the supplier's processes also produce variable results. If external suppliers are used, it is necessary to have protection against the worst excesses of their processes by ensuring compliance to precise and agreed specifications.

Variability acts across processes. Variability in one process can reduce the effects of variability in an interacting process. Much like an ocean wave rebounding off a cliff, variability between interconnected processes may act to calm the waters. Usually the opposite happens, where variability combines to produce problems of greater magnitude – instead of calm, a surging wave is created. This was the case in Example E3.1, where the international shipping line policies of not having fixed schedules and not providing regular container slots compounded the replenishment problems of its users. Variability that compounds problems requires identification and the offending processes redesigned to remove the negative impacts.

An example of a common process that compounds problems is when company purchasing policy requires the same item to be brought from several suppliers, in the questionable hope of keeping costs low through competition. They end up suffering more problems than does a company using only one supplier. The reason is that each supplier has their own process variability, and an item brought from many suppliers means you increase the variability problems in your business. This then requires corrective measures to be added to your processes to fix the problems caused by the suppliers' variability. Suddenly the small amount of money saved at purchase is dwarfed by the vast sums lost rectifying the troubles. By staying with one supplier you adapt your systems to their process variability, or you get them to modify their process to provide the product quality you want. To try and improve a range of suppliers of one item causes a great deal of effort and requires much time. Hence, it does not happen. Those companies with the mistaken belief that supplier competition reduces their costs have increased the variability problems for their business.

Variability introduces two failure scenarios for machinery and equipment. One arises when parts are at the extremes of material variability from poorly controlled production processes. These outliers may contain defects and weaknesses of one nature or another. When these parts are put into machines and equipment they suffer operational and environmental stress. If the capacity of the part is not up to the difficulties of the situation its defective weakness will cause it to prematurely and unexpectedly fail. The second failure scenario is when the part variability was well-controlled during manufacture, but the part is wrong for the duty; it cannot take the stresses and degradation of service. In such circumstances there is nothing wrong with the item, but it was selected for a situation beyond its capability and unexpected failure again occurs. Both these scenarios are the responsibility of the engineering design, reliability, procurement and maintenance groups to prevent.

Accepting process variability as inevitable is sensible, accepting the accompanying failure consequences as inevitable is disastrous. Proactive defect elimination and failure prevention is the most effective variability control methodology for reducing plant and equipment downtime. The best way to fix a problem is not to have it. To reduce the numbers of failures in your business introduce defect elimination and failure prevention into all your businesses processes.

#### 4. The Instantaneous Cost of Failure

Here are four headlines from newspapers and magazines of various industrial incidents over a six week period in Australia.

*“\$30 Million Refinery Glitch Stalls Fuel Users”* The failure of a flange on a key piece of processing equipment meant no gasoline was made for 2 weeks.

*“Liquefied Natural Gas Project Back On Track after Production Train Repairs”* Nine LNG shipments were missed during the event at a cost of \$300 million in lost profit.

*“Refuelling Problems Delay \$250 Million Airport Terminal Operation”* Jet fuel in the pipes at this airport had been contaminated with a protective anticorrosive coating left on the inside of the fuel pipes. Contaminated fuel would have gone into jet planes carrying thousands of people.

*“330 Hospital Patients Suffer Cold Winter Showers”* A steam boiler failed and was down for two days, putting the hospital at high risk of spreading infection to hundreds of its patients and visitors.

These failures made it to the news sheets. In a short six week period, in a lightly industrialised country, just four failures cost business hundreds of millions of dollars and put life at risk. How many failures happen that do not make the news? These real events indicate the huge financial and business consequences that arise from failure incidents. The cost of an incident may be no more than inconveniencing hospital patients, or it can be the cost of aeroplanes full of passengers falling out of the sky. The cumulative cost of equipment failure in industrial businesses, gauging from these four incidents over a six week period that made the newspapers, must be astronomical.

#### The Effect of Failure Incidents on a Business

Figure 4.1 is a simple accounting model of a business shown to every new accountancy student.

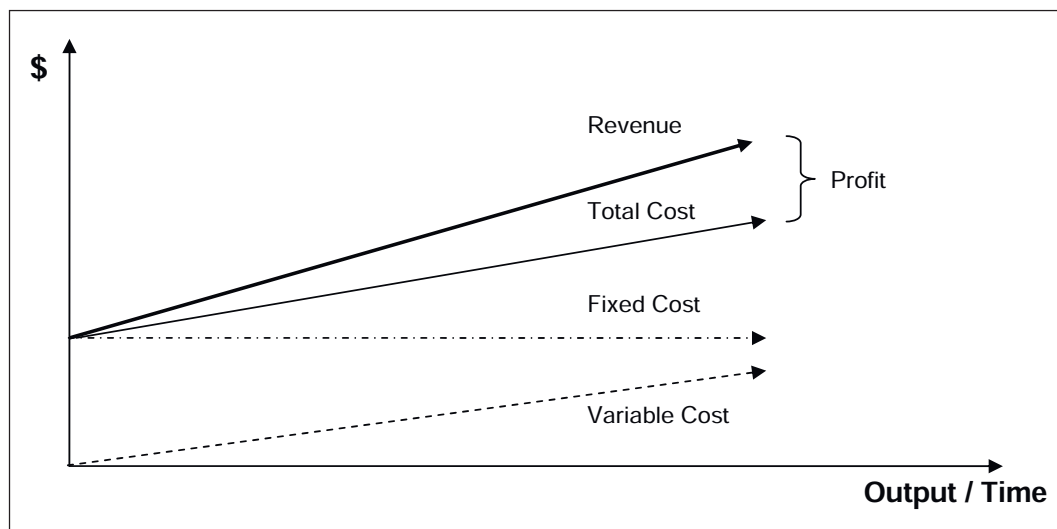


Figure 4.1 – Costs during Normal Business Operations.

When a business operates it expends fixed and variable costs to make a product that it sells for a profit. The business has fixed costs that it must carry regardless of how much it produces. These include the cost of building rent, the manager's salary, the permanent staff and employees' wages, insurances, equipment leases, etc. There are variable costs as well, such

as fuel, power, hire labour, raw materials to make product, etc. By doing business and trade it makes a profit. From the business model there are two simple accounting equations derived. The first equation below explains how to make money in business.

$$\text{Profit (\$)} = \text{Revenue (\$)} - \text{Total Costs (\$)} \quad \text{Eq. 4.1}$$

If the costs in a business are less than the revenue then the business is profitable. The next equation explains where expenses and costs arise in business.

$$\text{Total Costs (\$)} = \text{Fixed Costs (\$)} + \text{Variable Costs (\$)} \quad \text{Eq. 4.2}$$

In reality, the total cost equation above is incomplete since it hides the cost of waste in a business as a fixed cost or a variable cost. The complete total cost equation, which is not seen by new accountancy students, is below.

$$\text{Total Costs (\$)} = \text{Fixed Costs (\$)} + \text{Variable Costs (\$)} + \text{Cost of Loss (\$)} \quad \text{Eq. 4.3}$$

Equation 4.3 is frightening because it recognises there are needless losses and waste in a business. Normal financial accounting methods never identify such losses and they never show-up in monthly financial reports. All costs are either fixed or variable and viewed as the cost of doing business. No indication is made of the proportion of the costs that were wasted resources and money. Standard cost accounting methods identify variance from budget but they too do not calculate wasted and lost moneys. From the third equation it is possible to identify another equation that explains how to lose a great deal of money in business, even when trading profitably.

$$\text{Cost of Loss (\$/yr)} = \text{Frequency of Loss Event (/yr)} \times \text{Cost of Occurrence (\$)} \quad \text{Eq. 4.4}$$

$$\text{Risk (\$/yr)} = \text{Frequency of Event (/yr)} \times \text{Consequence of Occurrence (\$)} \quad \text{Eq. 4.5}$$

Equation 4.4 indicates the cost of loss and waste to a business is a real cost every time there is a loss occurrence – a failure of any type. Money is lost whenever loss and waste in all their forms occurs in a business. The more the number of loss events, or the more expensive the failures, the greater the financial loss. The ‘cost of loss’ equation is a risk equation, like that of Eq. 4.5. Together the equations warn that when you carry risks in your business, you also carry the likelihood of many losses.

Examples of failure and loss in a business are things done two or three times because it was done wrong the first time. Unplanned and unprepared tasks that take twice and three times what they should. Every safety accident which causes hurt or harm to people or an incident that harms the environment. Each time vendors supply the wrong materials. Each time wrong items go to customers. Every time plant and equipment breaks down. These are but a few examples of the effort, time and money lost in business due to failures. Every failure causes unnecessary problems and loss. They are preventable by controlling the responsible processes. Whether a failure is worth preventing is a financial decision based on the risks a business is willing to pay.

A failure incident causes an amassing of costs and the subsequent loss of profits. The cost of failure includes lost revenue, the cost of the repair, the fixed and variable operating costs wasted during the downtime and a myriad of consequential costs that reverberate and surge through the business. The organisation pays for them as poor financial performance. The costs of failure



are inescapable. They destroy business profits and health. Normal accounting practices do not measure the waste and loss of failures. Because accountants and managers do not see defect and failure total costs, little is done to stop them happening. Yet those losses send businesses broke. In order to see the effects of failure on a business, Figure 4.2 introduces a production failure into the model business of Figure 4.1.

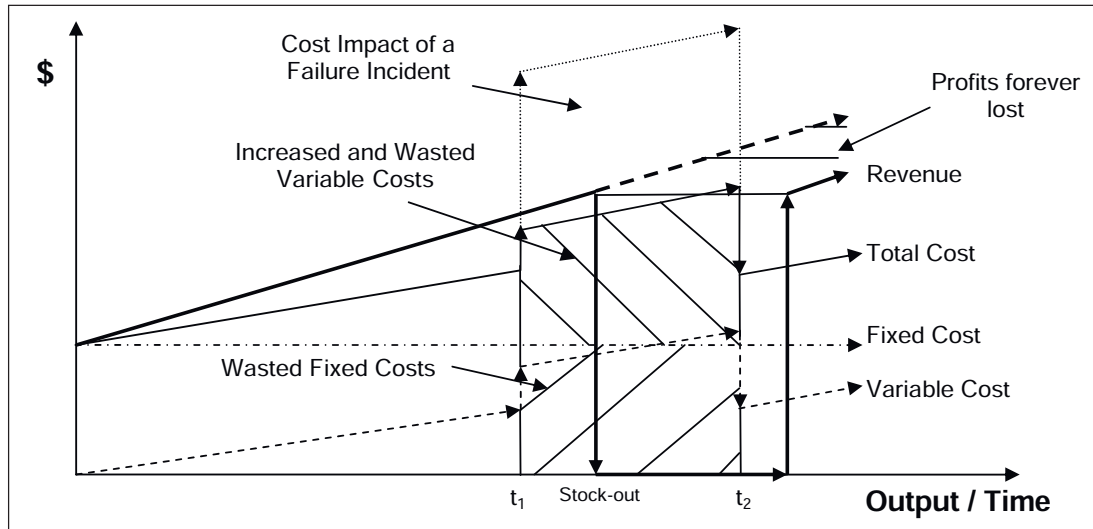


Figure 4.2 – Effects on Costs and Profit of a Failure Incident.

The failure incident stops the operation at time  $t_1$ . A number of 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 businesses 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  $t_2$ .

The cross-hatched areas in Figure 4.2 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 Figure 4.2) 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 spent. 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, which 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 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. Figure 4.3 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'.

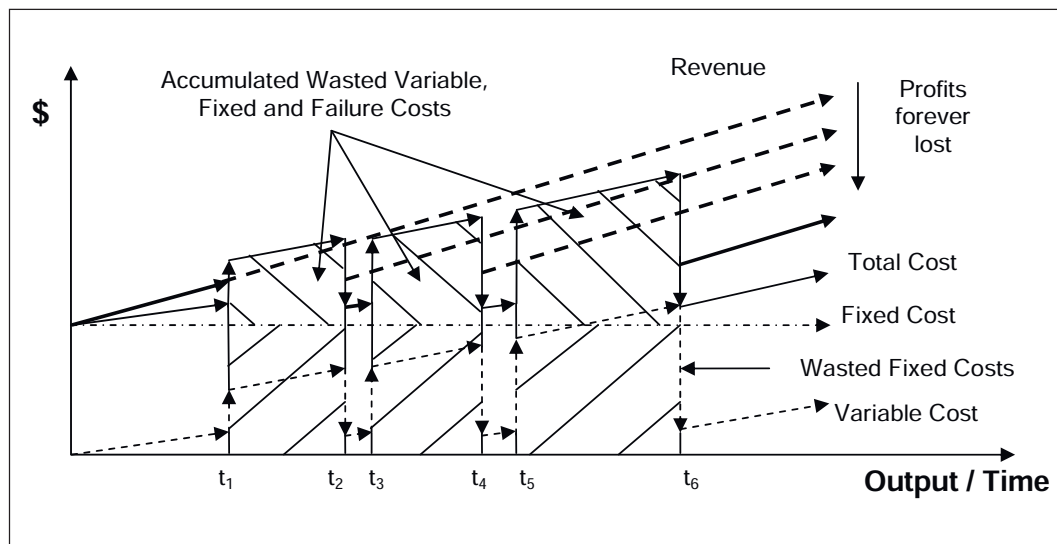


Figure 4.3 – Effects on Profitability of Repeated Failure Incidents (*Death of Many Cuts*).

The true cost of failure to a business is far bigger than 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.

### Failure Cost Surge

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, or those products scraped or reworked, or the cost to prepare equipment so it can be safely worked-on, or the cost of replacement raw materials for those 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 unavailable, people unable to work through injury, along with many other forfeited opportunities.

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 below reflect many of them. There may be other costs specific to an organisation in addition to those listed, and they also would need to be identified and recorded if you are to see the true defect and failure costs.

- Labour: both direct and indirect
  - operators
  - repairers
  - supervisory
  - management
  - engineering
  - overtime/penalty rates
- Product waste
  - scrap
  - replacement production
  - clean-up
  - reprocessing
  - handover/hand-back
  - lost production
  - lost spot sales
  - off-site storage
  - environmental rectification
- Services
  - emergency hire
  - sub-contractors
  - travelling
  - consultants
  - utility repairs
  - temporary accommodation
- Materials
  - replacement parts
  - fabricated parts
    - materials
    - welding consumables
    - workshop hire
  - shipping
  - storage
    - space
    - handling
  - disposal
  - design changes
  - inventory replenishment
  - quality control
- Equipment
  - OEM
  - energy waste
  - shutdown
  - handover
  - start-up
  - inefficiencies
  - emergency hire
  - damaged items

- Capital
  - replacement equipment
  - new insurance spares
  - buildings and storage
  - asset write-off
- Consequential
  - penalty payments
  - lost future sales
  - litigation and legal fees
  - loss of future contracts
  - environmental clean-up
  - death and injury
  - safety rectification
  - product recalls
  - idle production equipment
- Administration
  - documents and reports
  - purchase orders
  - meetings
  - meeting rooms
  - stationary
  - planning, schedule changes
  - investigations and audits
  - invoicing and matching
- Lost Value from Curtailed Lives
  - lost equipment/materials life
  - labour/resources wasted
  - outsourced services value lost

Figure 4.4 a symbolic representation of the Defect and Failure Total Cost (DAFT Cost) surge that reverberates throughout an organisation with each failure. Each failure strips profit from the business as resources marshal and divert from profit-making activities to combat the failure. The acronym 'DAFT' reflects how unnecessary and senseless these costs are.

### 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 outlay 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 sacrificed 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 full cost of all '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.

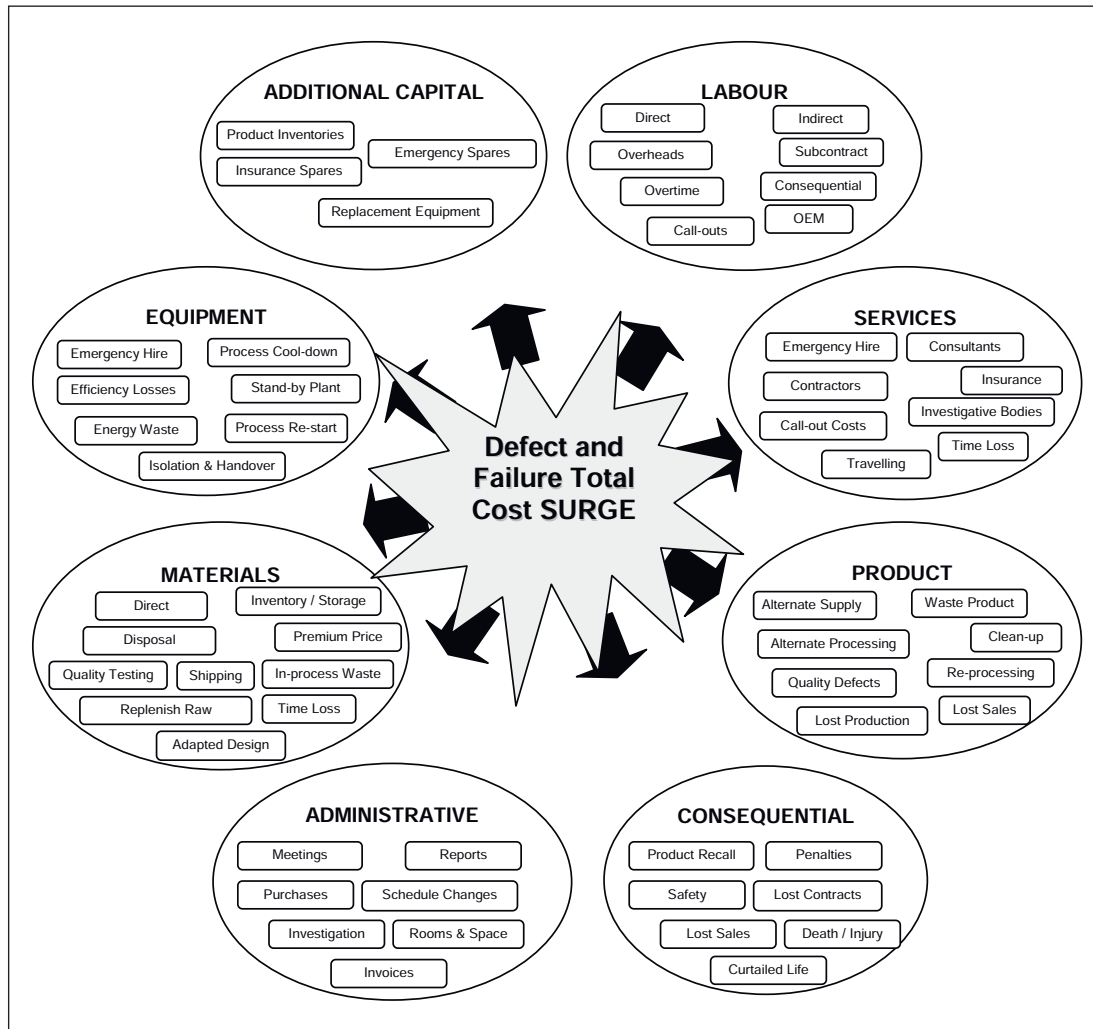


Figure 4.4 – A Multitude of Costs Arise and Profits are Lost Due to Defects and Failures.

### Detect Failures Starting to Minimise DAFT Costs

In fact, the requirement to spend moneys on repairs and rectification of a failure incident arises even before the failure. The loss and the obligation to spend money actually occur at the initiation of failure. Figure 4.5 shows the sequences of degradation once an equipment failure initiates. The failure may not happen for some days, weeks, months and even years, but once started a repair will be required. At the instance of every failure initiation, the organisation will eventually get a bill for its repair and correction. This cost would never arise if the failure sequence had never started.

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 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 cost is reduced through good preparation and scheduled at a convenient time to minimise production impact. Condition monitoring saves companies from breakdowns but it does not stop failure initiation. With condition monitoring an organisation may not suffer an equipment breakdown but they will still have to stop and do a repair. That work would not be necessary if failure did not start.

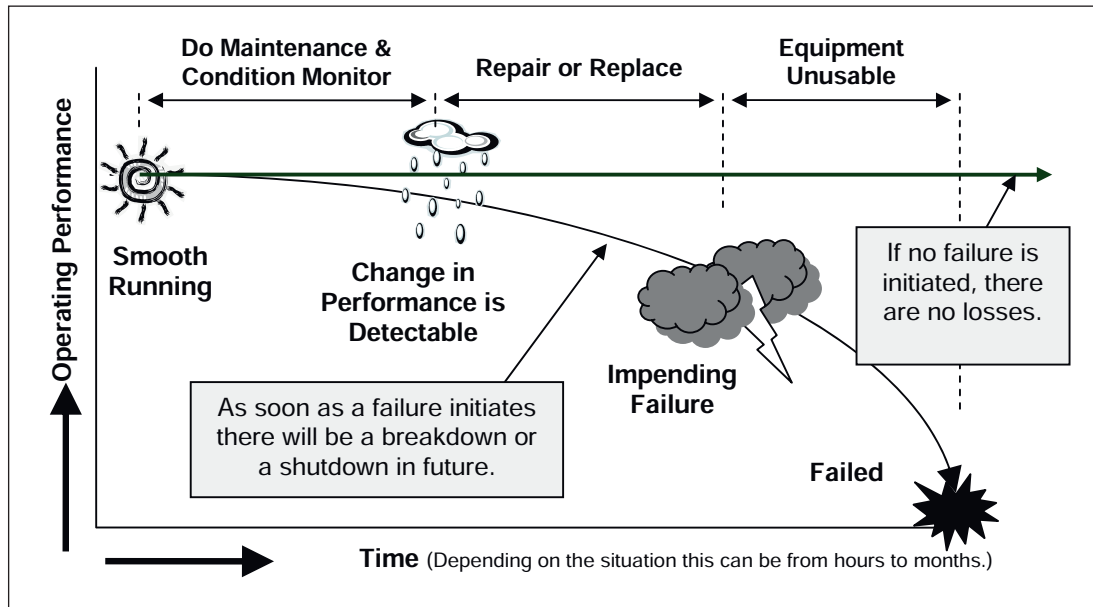


Figure 4.5 – Failure Starts Well Before it is Observable.

### Costing Failure Consequences

In order to justify preventing failures it is necessary to have a means to prove the total costs of a failure and show their full impact on an operation. Vast sums of money are 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 developing 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 Table 4.1 identifies the total costs. In this failure the inboard shaft bearing collapsed. The 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 supplier. 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 in Table 4.1.

To do 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 the costs are not yet collected. There are still more costs to be accounted for as shown in Table 4.2.



*Table 4.1 – Apparent Costs of a Pump Bearing Failure.*

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

Table 4.2 – Additional Costs of a Pump Bearing Failure.

Action No.	Description	Time minutes	Labour Cost	Other Cost/Loss
39	Control Room meets with Maintenance Leader.	10	20	
40	Control Room meets with repairmen over isolation requirements.	10	20	
41	Production Manager meets Maintenance Leader	5	10	
42	Production Manager meets Maintenance Manager.	5	10	
43	Production morning meeting discussion takes 5 minutes with 10 people management and supervisory present.	5	100	
44	Production Planner meets with Maintenance Planner	5	10	
45	General Manager meets with Production Manager	5	10	
46	Courier used to ferry inboard bearing as only one bearing was in stock.		30	
47	Storeman raises special order for bearing.	5	3	Included
48	Storeman raises special order for gaskets.	5	3	Included
49	Storeman raised special order for stainless shims used on pump alignment but has to buy minimum quantity.	5	3	250
50	Storeman raises order to replenish spare bearing and raises reorder minimum quantity to two bearings.	5	3	125
51	Storeman raises order to replenish isolation tags.	5	3	5
52	Crane driver worked over time.	300	200	
53	Both repairmen worked overtime.	600	400	
54	Extra charge to replace damaged/soiled clothing.			100
55	Lost 200 liters of product drained out of pump and piping.			100
56	Wash down water used 1000 liters.			10
57	Handling and treatment of waste product and water.	15	10	20
58	Pump start-up 75 kW motor electrical load usage.			5
59	13.7 hours of lost production at \$2,500/hour profit.			32,000
60	Account clerk raises purchase orders, matches invoices; queries order details, files documents, does financial reports. Paper, inks, clips,	60	40	20
61	Storeman answer order queries.	20	13	
62	Maintenance workshop 1000 watt lighting on for 10 hours.			150
63	Two operators standing about for 13 hours	750	1000	
64	Write incident notes for weekly/monthly reports	30	30	
65	Incident discussed at senior levels three more times.	15	30	
66	Stocks of product run down during outage and production plan/schedule altered and new plan advised. Paper, inks, printing	30	30	10
67	Reschedule deliveries of other products to customers and inform transport/production people.	30	20	10
68	Ring customers to advise them of delivery changes.	30	20	50
69	Electricity for lighting and air conditioning used in offices and rooms during meetings/calls.			50
	<b>TOTAL OF EXTRA COSTS</b>		<b>\$2,018</b>	<b>\$32,905</b>

The true cost of the pump failure was not \$1,320; it was \$36,243 – 20 times more. The maintenance 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.



## **Introduction to Defect and Failure Total Costing**

Conducting a thorough analysis into a failure means compiling the total and complete financial costs of the failure incident and its consequences. The process of collecting, analysing and reporting all costs due to a failure is known as the Defect and Failure Total Costs method. DAFT Costing puts the Instantaneous Cost of Failure into a formalised accounting process. It shows the vast amounts of money wasted throughout an organisation from failure. To assist in compiling the DAFT Cost list it is useful to use the company's Chart of Accounts, as it contains all the accounting codes used to allocate costs and charge payments in the organisation. New cost centres usually need to be developed to capture all Defect and Failure Total Costs. The methodology brings together the Financial, Production, Engineering and the Maintenance groups in cooperation. It provides a means for these normally separate groups to work together to solve company problems.

## **Calculating DAFT Cost using Activity Based Costing**

The DAFT Cost methodology is Activity Based Costing applied to a single failure incident. The intention being to identify the total true cost of failure and either accept such failures in future, or put into place mechanisms and systems to stop them happening. Activity Based Costing (ABC) is an accounting technique that identifies the total and complete costs of the activities undertaken to perform a function and produce a product. ABC applied to DAFT Costs allows an organisation to determine the actual cost of all resources and services used by a failure. It is a powerful tool for measuring failure costs since it itemises every expense and identifies its make-up. The aim is to trace the cost of every action and task caused by the failure event throughout the organisation.

## **Steps for Performing DAFT Costing**

Below is overviewed the ABC process used for DAFT Costing. The steps followed during the process are:

- |                              |                              |
|------------------------------|------------------------------|
| 1. Identify Activities       | 4. Analyse Costs             |
| 2. Gather Costs              | 5. Finalise Costs and Report |
| 3. Trace Costs to Activities |                              |

One person can perform these steps, or in the case of a sufficiently large incident, a small core team of people is committed to work on the project. Additional support can come from others in the organisation, or from consultants. The investigation and costing process can take anywhere from a few days to a few weeks. It depends on the scale of the incident, the level of detail required, complexity of an organisation's processes, and commitment of team resources. The investigation ought to be managed as a project using established and sound project management tools and techniques. Details of each step are noted below.

## **Identify Activities**

Specify the scope of the investigation and address issues such as the following:

- i. The period of time (start, length and end) over which the incident is investigated
- ii. How the investigation is resourced
- iii. How long to spend on the analysis before a final report is provided

- iv. The business and production processes to be investigated
- v. The costs centres to be analysed
- vi. Development of the costing table contents
- vii. Identifying who is to be interviewed to get a complete picture of the losses and costs

The depth and detail of analysis depends by the extent of the activity breakdown and the available resources. The core team develops DAFT Cost tables, selects key people to interview, collects activity information and identifies all costs related to the failure. The departmental groups involved in the incident and its consequences should be included in setting the scope.

### **Gather All Costs of Failure**

Gather costs for each material and service activity purchased or lost because of the failure. These costs include salaries and wages, expenditures for parts and materials, replacement machinery, hire equipment, etc. Get documented confirmation of all costs so future disputes and queries can be readily resolved. Trace costs right back to invoices and wages records where possible. These provide undisputable proof of the real costs. When documents for the true costs incurred are not available, use cost assignment formulas based on the costs of similar other activities.

### **Trace Costs to Activities**

In this step, tabulate the identified costs to produce the total cost for each failure activity by organisational department.

### **Analyse Costs**

For this step, use the activity costs from the tables to identify where the money went. A cost map (see Process Step Contribution Mapping) maybe useful, along with various Pareto charts to identify the proportion of costs by activities, and the amount of resources they consumed.

### **Finalise Costs and Report**

Lastly, produce a succinct final report on the total costs of the failure, its effect on the organisation's resources and productivity and the resulting activity costs incurred by the incident.

### **How to Develop DAFT Cost Tables**

The steps to follow in creating a DAFT Cost table are:

1. Identify each organisational department and work group involved in the incident.
2. Identify every person in each department and work group involved in, or affected by the incident. Determine what they did during the incident and the total normal time and penalty time spent, or lost, on incident related activities.
3. Get people's gross hourly normal time and penalty time cost. The gross hourly cost typically includes an overhead component of all fixed operating costs, administrative, engineering and management costs. This overhead is on-top-of base salary package or wage package. For shopfloor employees the gross cost is often over twice the hourly pay rate. If the pay rates do not include an overhead component, you will need to calculate it and add it to the rate.

4. Identify every organisational process disrupted by the incident. This includes manufacturing processes and all business and administrative processes such as accounts receivable, secretaries, inward goods receipt, forklift drivers, etc. Identify every labour cost.
5. Find each purchase order due to the incident and see what it brought. Interview persons involved with the incident to identify all materials and resources purchased or used.
6. Identify every material scrap and waste resulting from the incident. Even if salvageable, it is an extra cost incurred because of the incident. Calculate the cost of the material to that point in the process, e.g. cost per kilogram, cost for tonne, cost per part, cost per metre, etc.
7. Identify all rework costs for salvageable materials per unit measure of the material, e.g. cost per kilogram, cost for tonne, cost per part, cost per metre, etc.
8. Include the expected revenue from sales of all products normally made but stopped by the failure. Production not intended for sale is not included as a failure cost, as there is no opportunity cost lost. If production not made because of the failure causes loss of a current customer, or loss of a definite new customer, count the foreseeable revenue lost as a cost.
9. On repaired and replaced plant and equipment, identify the wasted proportion of part's lives for any parts previously replaced because of the failure. The curtailed lives had value. If they worked to the end of their natural 'wear-and-tear' life no value was lost. If they failed before their natural end, estimate the value of material, labour and subcontract services wasted.
10. On a spreadsheet, create the DAFT Cost tables.

Examples of the spreadsheet columns and listings used to capture failure costs in a manufacturing organisation are in Tables 4.3 through to 4.7. A sample DAFT Costing table is in the MS Excel spreadsheets in the CD accompanying this book.

### **Labour Costs**

- Start a worksheet to capture labour costs.
- In the first column, list each department involved.
- In the second column, list each department process affected.
- In the next column, list the position title of each departmental employee affected in each process. The same employee may appear more than once.
- In the fourth column, indicate all work they did because of the incident. If it was more than one task, record them all in individual rows. If they did other duties that were unnecessary work, but occupied their time, then record those as well.
- Beside that column, list their gross normal shift hourly rate.
- In the next column list the total normal shift hours worked, or portions of an hour e.g. 0.25, 0.5, for each person involved on, or affected by the incident.
- In the column beside, list their penalty shift hourly rates.
- In the next column list the total shift hours worked at penalty rates, or portions of an hour e.g. 0.25, 0.5, for each person involved on, or affected by the incident.
- In the final column, calculate the total cost of all labour.

Table 4.3 – Labour Costs Incurred by the Organisation Due to a Failure.

Labour Costs Incurred Because of a Failure Incident								
Dept	Dept Process Affected	Employment Position Affected	Work Done	Normal Hourly Gross Rate	Total Normal Hours	Penalty Hourly Gross Rate	Total Penalty Hours	Total Labour Costs
Production	Process Line 1	Equipment Operator 1	Clean-up					
			Set-up again					
		Equipment Operator 2	Clean-up					
			Set-up again					
		Production Supervisor 1	Inspect Failure					
		Production Manager 1	Inspect Failure					
Maintenance	Mechanical	Trades Fitter 1	Strip Machines for Clean-up					
		Trades Assistant 1	Assist Fitter					
		Maintenance Supervisor 1	Inspect Repair					
	Electrical	Electrician 1	Remove burnt control panels					
			Install new control panels					
		Electrical Supervisor 1	Inspect Repair					
	Stores	Storeman 1	Receive/ store new panels					
		Maintenance Engineer 1	Inspect Failure					
			Inspect Repair					
		Maintenance Manager 1	Inspect Repair					
		Secretary 1	Compile failure report					
		Senior Executive Manager 1	Attend site meeting					
Finance		Accounts Receivable 1	Process purchase orders/ invoices					
TOTAL COST								

### Purchased Materials and Services

- Start a second worksheet to capture purchases of materials, goods, hire equipment, subcontractors, service specialist, etc.
- In the first column list, each department involved.
- In the second column list, each department process affected.
- In the third column, list all the plant, equipment and machinery affected by the incident. The costing goes as far as recognising the use of printing paper and ink for reports.
- In the fourth column, list the materials and purchased services used.
- In the next column, list all invoiced cost, or portions of invoiced costs, for every plant, equipment and machinery affected by the incident.
- In the final column, calculate the total cost of all purchases.

*Table 4.4 – The Purchased Materials/Services Costs Incurred Due to a Failure.*

<b>Purchased Material's and Service's Costs Incurred Because of a Failure Incident</b>					
<b>Department</b>	<b>Department Process Affected</b>	<b>Plant, Equipment and Machinery Affected</b>	<b>Parts, Materials, Services Purchased</b>	<b>Total Invoiced Purchases</b>	<b>Total Labour Costs</b>
Production	Process Line 1	Manufacturing Equipment 1			
		Manufacturing Equipment 2	Electrical Control Cabinet		
			Electrical Motor Draw		
			Electrical Cable		
			Process Computer Programmer		
		Manufacturing Equipment 3			
		Forklift 1			
		Production Building 1	Power Supply Cabinet		
Maintenance	Mechanical		Mechanical Consumables		
			Nuts and Bolts		
	Electrical		Electrical Consumables		
	Stores	Facsimile	Paper		
Administration		Printer	Report Materials – Paper, ink, binder		
		Facsimile	Paper		
Finance		Printer	Purchase Orders		
<b>TOTAL COST</b>					

### Material and Product Wastes

- Start a third work sheet to capture material and product waste costs.
- In the first column, list each department involved.
- In the second column, list each department process affected.
- In the third column, list all the plant, equipment and machinery affected.
- In the fourth column, list each item of material waste identified for the equipment.
- In the fifth column, list the unit cost of each waste at its value to that point in production, e.g. cost per kilogram, cost for tonne, cost per part, cost per metre, etc. Add any additional unit cost for rework of salvable items to the initial value.
- In the next column, indicate how much of each waste unit was present.
- The final column calculates the total of all the material wastes.

*Table 4.5 – Material and Product Waste Due to Failure.*

<b>Material's and Product's Waste Costs Incurred Because of a Failure Incident</b>						
<b>Department</b>	<b>Dept Process Affected</b>	<b>Plant, Equip and Machinery Affected</b>	<b>Materials, Products Wasted or Reworked</b>	<b>Unit Cost of Waste and Rework</b>	<b>Total Wasted / Reworked Units</b>	<b>Total Waste Costs</b>
Production	Process Line 1	Manuf Equip 1	Raw Materials for the Line	Cost per kilogram		
			Product in Equipment 1	Cost per unit		
		Manuf Equip 2	Product in Equipment 2	Cost per unit		
		Manuf Equip 3	Product in Equipment 3	Cost per unit		
		Forklift 1				
		Production Building 1				
Maintenance	Mechanical					
	Electrical					
	Stores	Facsimile				
Administration		Printer				
		Facsimile				
Finance		Printer				
<b>TOTAL COST</b>						

## Lost Opportunity Costs

- Start a fourth work sheet to capture lost opportunity costs.
- In the first column, list each department involved.
- In the second column, list each department process affected.
- In the third column against each process, record the opportunities not taken because the incident prevented the taking of them. Such opportunities as:
  - lost sales that would have definitely happened,
  - double handling of which the second handling prevented normal work,
  - production volume lost due to downtime, rework, time lost due to cleaning down of equipment and production lines
  - Medical expenses for accident victims
- In the next column indicate the unit cost of each lost opportunity, e.g. cost per kilogram, cost for tonne, cost per part, cost per metre, etc.
- In the next column, indicate how much of each lost unit was present.
- The final column calculates the total of all the lost opportunities.

*Table 4.6 – Opportunity Lost Costs Incurred Due to a Failure.*

Opportunity Lost Costs Incurred Because of a Failure Incident					
Department	Department Process Affected	Opportunity Lost	Unit Cost of Lost Opportunity	Units Lost	Total Opportunity Lost Costs
Production	Process Line 1	Profit on sales from 24 hours of lost production			
		Curtailed Lives of repaired and replaced equipment			
Maintenance	Mechanical				
	Electrical				
	Stores				
Administration					
Finance		Moneys for Process Line 1 cost reduction spent on repair			
Sales	New Customer	Future sales revenue			
<b>TOTAL COST</b>					

## Summary of Costs

- On a separate worksheet develop a summary spreadsheet, such as Table 4.7, showing the separate cumulative cost for each category and the grand total cost.

## 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.

*Table 4.7 – Summary of Costs Incurred Due to a Failure.*

<b>Summary of All Costs Incurred Because of a Failure Incident</b>	
<b>Cost Categories</b>	<b>Final Cost</b>
Labour Cost	
Materials and Services Purchased Cost	
Materials and Products Wasted Cost	
Opportunity Lost Cost	
<b>GRAND TOTAL DAFT COST</b>	

## 5. Preventing Life Cycle Risks

All that you have read so far needs to be put into a methodology for delivering the right project design, operating practices and maintenance that produce maximum life cycle profits. Operating plants and machines rely on us to get their working conditions right for them. The best strategies for improving reliability are those that extend the life of parts. When machine parts live and work in conditions that limit stress levels to values that deliver long operating lives, they can return maximum reliability to us.

We have considered the foundation understandings needed to grasp the issues facing us in attempting to improve equipment reliability. These are:

- recognising that all machines and all work activities are series processes and that the success of every series process depends on doing each of its steps successfully;
- recognising the limitations of the physics of the materials used in the parts that make our plant and equipment, and the need to keep stresses well within the plastic deformation range of the materials-of-construction;
- identifying that variation away from the standard for best performance is what causes failure, and that if we want right results we must use processes with natural variation always within the outcomes that deliver excellence;
- recognizing that the costs of defect and failure are directly connected to the amount of risk carried by a business – the more risks tolerated, the greater the opportunity for errors, and the higher the costs, losses and wastes that must eventually accrue;
- appreciating that failure events do not only have localised consequences, rather failure surges company-wide. A business never escapes from paying for all the costs of its failures.

Figure 5.1 is an overview of the Plant and Equipment Wellness Methodology. It is a process to arrive at the right design, operating and maintenance strategies for maximising equipment reliability. The methodology takes a life-cycle view of plant and equipment and recognises that a lifetime of high reliability starts by controlling the design and selection of the equipment. It helps you to develop the right engineering, selection, construction, operational and maintenance plans and practices for your plant and equipment. Always you are trying to get the maximum life for the parts. If the parts do not fail, the equipment does not stop. With fewer risks to parts, there will be fewer failures. You improve equipment reliability by using the Plant and Equipment Wellness Methodology to reduce, control and manage the number of risks presented to your equipment over its lifetime.

The fundamental driving philosophy is to continually reduce the risks carried by critical working parts. These are the parts that stop a machine if they fail. By relentlessly reducing the likelihood of things going wrong to the working parts the equipment reliability naturally improves because its parts carry lower and lower chances of failure. The methodology forces you to work-out how to prevent risks to operating equipment parts arising in the first place. It requires that you action that risk prevention and make it a major part of your design, operating and maintenance philosophy.

### Start with a Process Map of the Situation

Whether you are improving a work process or on an equipment item, the process map is a 'picture' of how a thing works. Drawing a process map of a situation lets you understand the weaknesses in the process. Figure 5.2 is a process map of the life-cycle of plant and equipment shown in Figure 1.13.



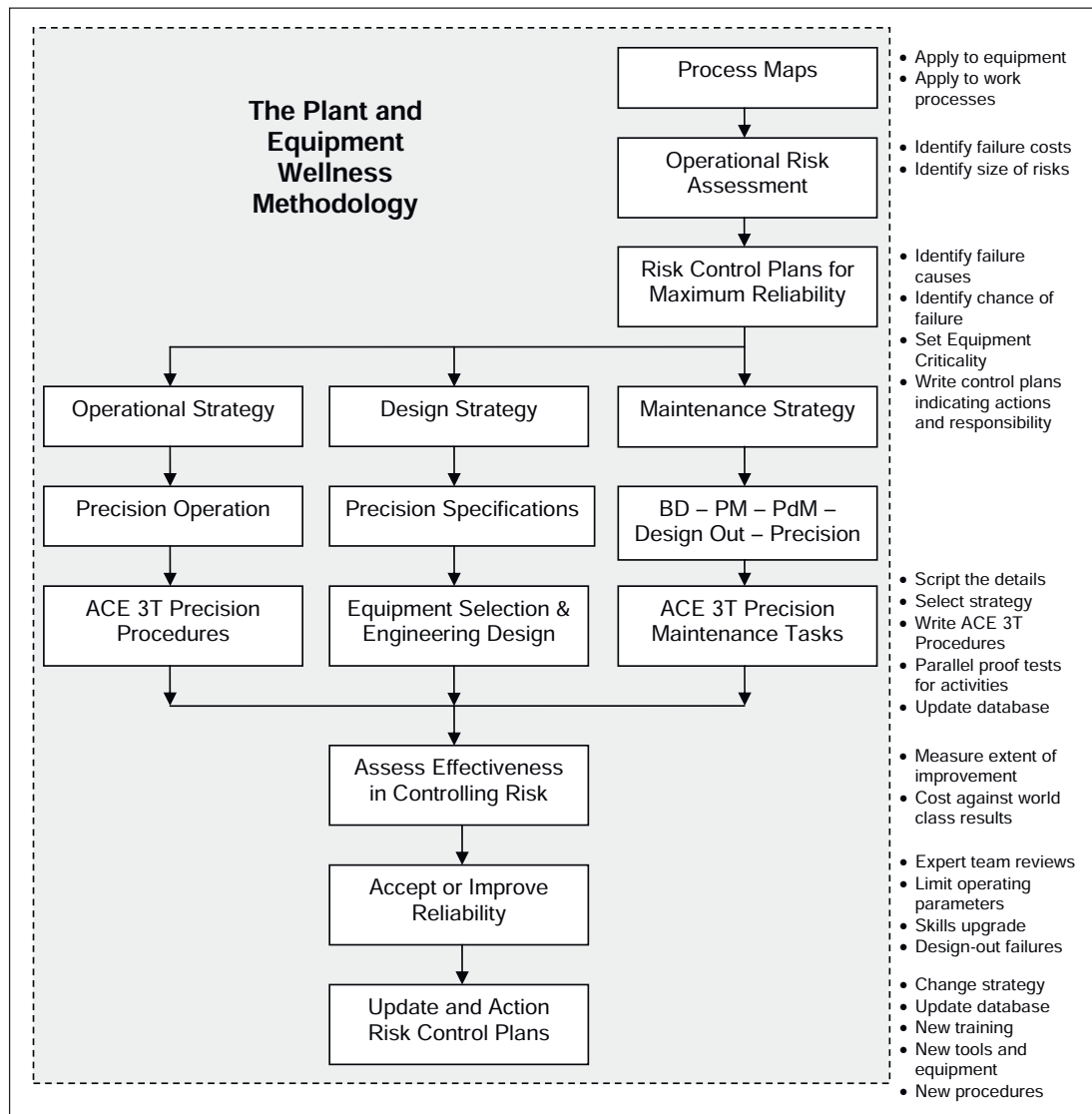


Figure 5.1 – Controlling Operating Risk with the Plant and Equipment Wellness Methodology.

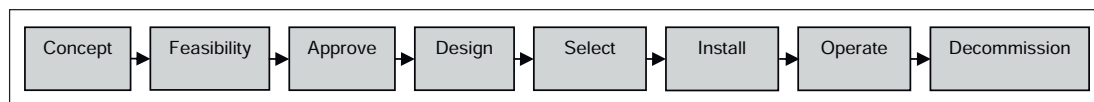


Figure 5.2 – A Process Map of the Equipment Life Cycle.

Without the process map it would be difficult to imagine a life cycle, much less find its weaknesses. As a map, the life cycle of plant and equipment is now drawn in a form that allows risks to be identified, analysed and discussed. The map immediately shows-up the great weakness in the life cycle – it is a series arrangement. Using a process map, whether it is for a work process, production process or the parts in a machine, lets you ask the right questions that lead to understanding and reducing risk. It is the start of all equipment reliability and business process improvement strategies.

## Equipment Process Maps

The equipment process map is used to identify what is required for highly reliable parts and assemblies and starts the process of developing strategies to provide those outcomes. Maximising the reliability of equipment requires identifying and controlling the operating risks added at every stage of design, installation and operation. Removing them where possible and unrelentingly reducing them if not.

Figure 5.3 is a series of process maps for a centrifugal pump-set ‘picturing’ the equipment’s construction and operation. It helps you identify where failures will stop the equipment working. With it you spot the risks to its operation by asking at each step along the process – “If this step fails, how will it affect the outcome of the process?” Once we know the risks that can stop the process, we can put the right plans and actions into place to prevent and reduce those risks.

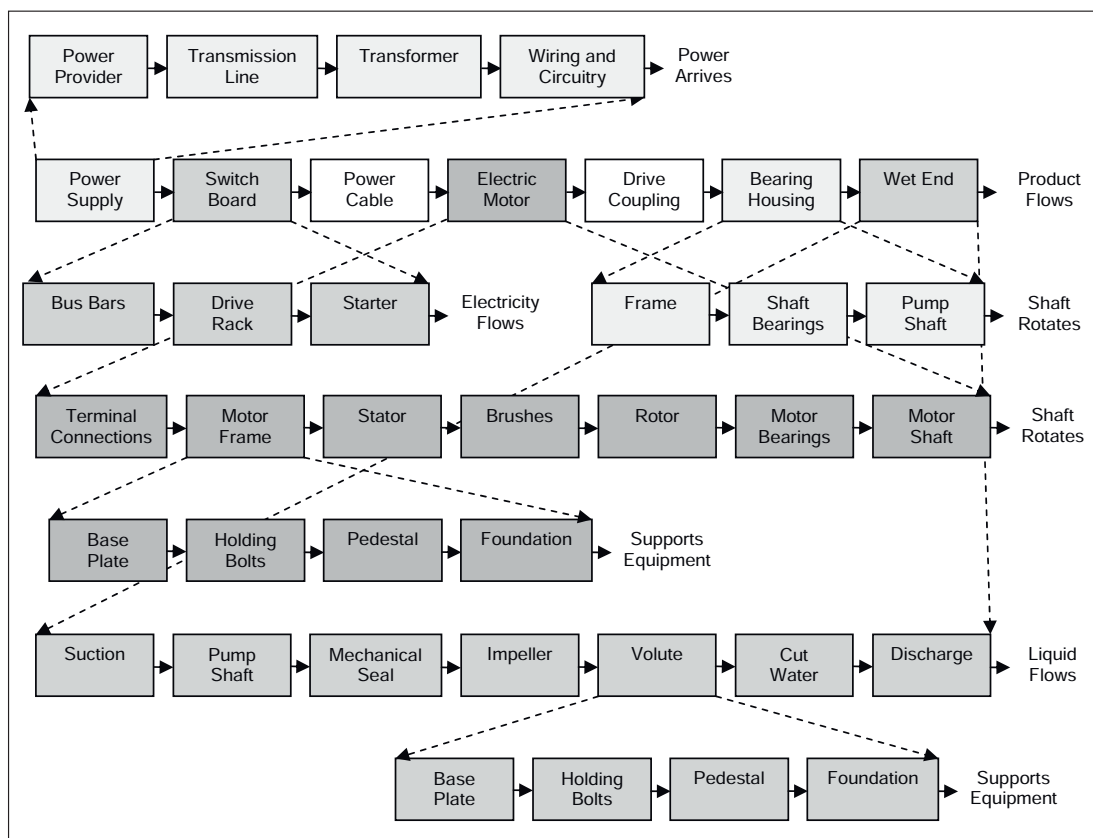


Figure 5.3 – A Process Map of a Centrifugal Pump-set Delivering Product.

The equipment process maps are made detailed enough to use them to identify the operational risks on the equipment being examined. For example, the mechanical seal in the wet-end does not have a process map. When the working parts of a mechanical seal fail the whole seal becomes unusable and the pump must be stopped. To identify the consequent impact of seal failure on the pump we do not need to know every way that a mechanical seal can be failed. We only need to realise that when the seal fails so does the pump. Similarly, the shaft drive coupling does not have its own process map because the box on the diagram sufficiently represents the part for identifying the risks it causes to the pump, should it fail.

Normally, process mapping is sufficient if it identifies the presence of operational risk to an equipment assembly. In some cases you may want to process map an assembly right down to

its individual parts and investigate the risks each part carries. You could expand the ‘wiring and circuitry’ box in Figure 5.3 to find the risks carried by individual components in the power supply system. If it became necessary to understand what can cause the mechanical seal or the coupling to fail, the process map of the assembly is drawn and analysed to identify the risks carried by its own individual parts.

Expanding a process map to include more equipment assembly details is encouraged when it is not certain how far to take the mapping. For example, it is necessary to expand the electric motor frame and volute to include the supports because a solid base is critical to the operating life of the pump-set. It is important to know the risks the supports carry, as their failure will fail the pump-set. Expanding an item on a process map forces people to consider the risks it carries. If items are left-off a process map there will be no purposeful risk controls installed to protect the equipment.

Using a process map provides us with one more powerful perspective for risk analysis. We can perform ‘what-if’ analysis and visualise the effects of multiple causes of failure acting together. Such as, ‘If the motor frame is loose on its support, what else will it affect?’ or ‘What if the power cable has a cracked sheath, how will it affect the pump-set foundation, or the motor bearings, or the mechanical seal?’ We are better able to appreciate consequential failures from remote causes.

Here are some guidelines to help develop a useful process map flow sequence.

- Follow the energy flow. Draw maps starting from the energy source and follow the process through to the lowest energy level. E.g., the energy from the electric motor travels through the motor shaft, the coupling and into the pump shaft.
- Follow the path of the force. From the location a force is applied, follow the force and loads to the final points of restraint. E.g., the holding bolts restrain the power generated by the electric motor driving the pump in Figure 5.3.
- Follow the product flow. Start mapping at the point product enters and follow the process through to where the product leaves. E.g., the liquid moving through the pump enters at the suction nozzle and leaves at the discharge nozzle.

Because most equipment types are used repeatedly in industry, once you have the first process map for a type you can copy it again and again. Alternating current (AC) electric motors are an example. You can reuse the process map for AC electric motors over a large range of sizes. A 5kW AC electric motor would have the same process map as an 11kW electric motor. This saves time analysing all AC electric motors in an operation. You would not use an AC electric motor process map for a hydraulic motor. They are not identical. The hydraulic motor works in a totally different way to an AC electric motor. The hydraulic motor needs its own process map. But once drawn the process map can be used again for similar hydraulic motors and adjusted for peculiarities.

### **Work Activity Process Maps**

Work tasks and activities that impact on operating plant and equipment are also process mapped. If job procedures are available, convert them into process maps. An example of a process map for a clerical task recording important cost information is shown in Figure 5.4. The tasks in the process map are intentionally drawn across the page so that ‘Lean’ value stream mapping can be applied later. Where job procedures are not available, ask people what they do and record the steps they actually follow (not what they say they do). From the description, develop the work activity process map.

## Identify and Write Down the Process Step Risks

The next step is to identify the risks that are present for each box on the map. For each box perform a risk analysis and develop risk management strategy, plans and actions. Later you will develop a written plan to reduce the causes of unacceptable risks.

## Equipment Risk Review

A risk identification table for production equipment is developed in two separate steps.

List equipment, assemblies and sub-assemblies in a risk identification table like Table 5.1. As the Plant and Equipment Wellness methodology progresses the table listing eventually grows into the maintenance strategy for the operation. 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. They ask 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.

The team completes a risk analysis, recording in a risk identification table likely risks to equipment, the impact if the worst was to happen, along with the associated DAFT Cost and any explanatory comment. There is no need to record a failure cause if team consensus is that it cannot happen. But if one team member wants the cause recorded, then do so. Number each entry uniquely so it can be identified and referred to in future correspondence and discussion.

The second step uses the equipment failure history for the equipment. From the maintenance work history in the CMMS (Computerised Maintenance Management System) or documented history records, go through equipment by equipment and identify any other type of failure not recorded in the team review. In this step it is also worth counting the number of each type of failure, and the dates they occurred for later reliability analysis. More information on how to do this is available in Chapter 17 – Mining Your Equipment History.

## Work Process Risk Review

Work done by human beings can be wrong. We need to identify, prevent and control risks that arise from human error. The risk identification method used for equipment is also used to identify human error and work quality risks in work processes. The tasks and actions on the work process map are written into a spreadsheet table. Each step is analysed to find the risks and identify parallel test activities, or error-proofed methods, to stop them going wrong. If human error cannot be prevented it is necessary to reduce the consequences of the error. Table 5.2 lists the work process of Figure 5.4, the monthly cost report, as an example of identifying human-error risks in workplace processes. Usually risk control actions and parallel proof-tests are self-evident and are written into the table as it is developed.

## Analysing Project Design Operational Consequences

Equipment life cycle cost includes the capital cost and subsequent lifetime operating costs. To lower operating cost we need to remove risk from the working parts by providing healthy operating conditions and reduced stress levels. We get maximum operating reliability and operating profit if this is done as part of the capital project. Figure 5.5 shows the phases of a typical project and the points during its life that the future operating costs are committed <sup>30</sup>. Clearly the decisions and

Table 5.1 – Risks Identification Table Layout for Pump-set Parts and Assemblies.

Equipment	Assembly	Sub-Assy or Parts	Sub-Sub Assy or Parts	Risks - Possible Causes of Failure	Effects of Worst Likely Failure	DAFT Cost of Worst Failure	Comments
Pump-set 01							
1	Power Supply			1 Power Provider failure	1 Downtime	\$100,000	\$25,000 per hour Minimum 4 hours if power is turned off
				2 Lightning strike	1 Downtime	\$200,000	Minimum 8 hours if power is lost due to failure
2	Switch Board			1 Fire	1 Downtime	\$200,000	
				2 Liquid ingress	1 Downtime	\$200,000	
				3 Impact	1 Downtime	\$200,000	
3		Panel Connection		1 Loose clamp bolts	1 Fire in switchboard		
				2 Poor cable crimping	1 Fire in switchboard		
4		Drive Rack		1 Dust from Product	1 Fire in switchboard		
				2 Poor assembly	1 Fire in switchboard		
				3 Rust into place	1 Downtime		
5		Motor Starter		1 Overload	1 Downtime		
				2 Short circuit	1 Major electrical burn		
6	Power Cable						
7	Electric Motor						
8		Connection					
9		Motor frame					
10			Base Plate				
11			Holding Bolts				
12			Pedestal				
13			Foundation				
14			Stator				
15			Brushes				
16			Rotor				
17			Bearings				
18			Shaft				
19	Drive Coupling						
20	Bearing Housing						
22		Shaft					

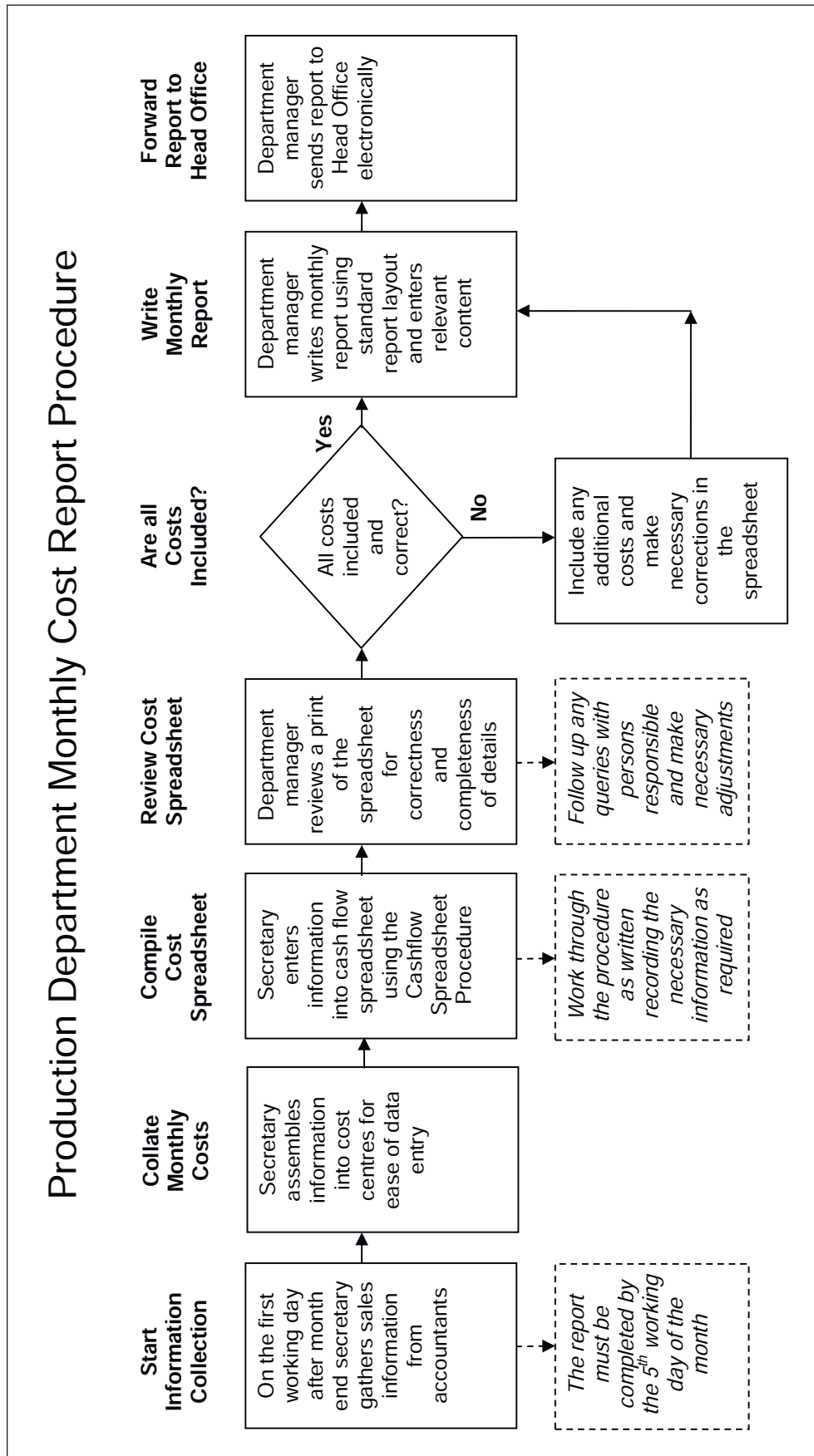
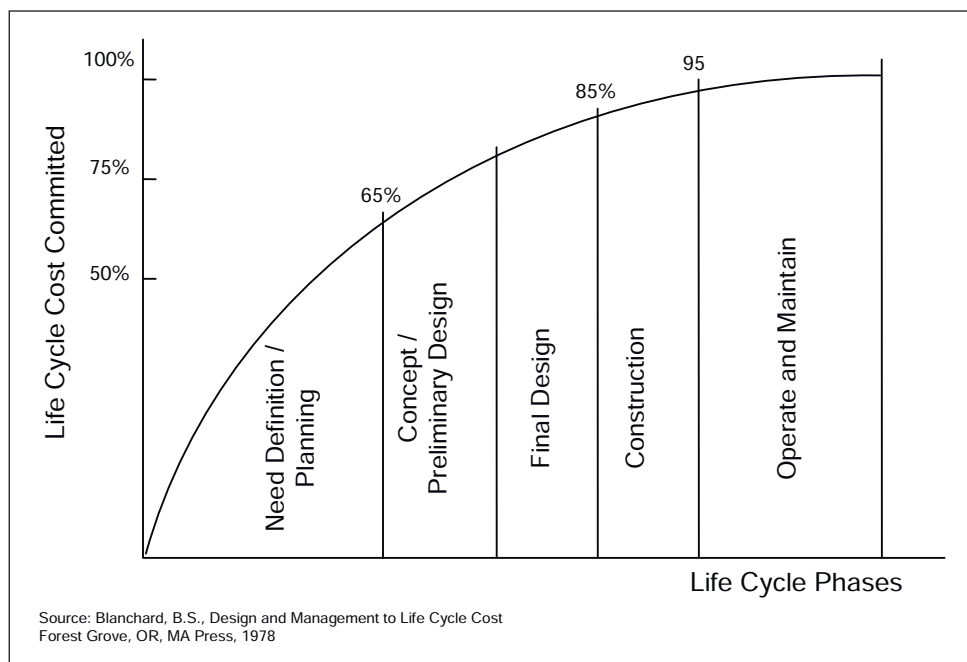


Figure 5.4 – A Job Procedure Converted into a Work Process Map.

selections made during the project conception and design phase sets the vast majority of the future operating costs. Poor design choices plague an operation all its life. H. Paul Barringer, P.E., an internationally renowned reliability expert, provides further confirmation of the profound effect on operating costs that result from design decisions in this extract from his paper titled ‘Life Cycle Cost and Reliability for Process Equipment’<sup>31</sup> – “Frequently the cost of sustaining equipment is 2 to 20 times the acquisition cost. Consider the cost for a simple, continuously operating, pump – the power cost for driving the pump is many times larger than the acquisition cost of the pump. This means procuring pumps with an emphasis on energy efficient drivers and energy efficient rotating parts while incurring modest increases in procurement costs to save large amounts of money over the life of the equipment. Here is an often cited rule of thumb: 65% of the total Life Cycle Cost is set when the equipment is specified!! As a result, do not consider specification processes lightly – unless you can afford it.”



*Figure 5.5 – Life Cycle Cost Commitments.*

### **Design and Operations Cost Totally Optimised Risk (DOCTOR)**

Project groups have the power to build great businesses or just ‘also-ran’ businesses. When they design a plant, select its equipment, build and install it, the project group are creating a future successful operation, or a painfully drawn-out failure. Project groups need a financial tool to visualise the impact of their decisions on the future success of the business they are creating. One tool they can use to successfully improve operating profits is called ‘Design and Operations Cost Totally Optimised Risk’. Its acronym is DOCTOR and uses DAFT Costing to optimise the design and selection of project equipment and plant designs based on future consequential operating costs and failures. Figure 5.6 represents the process applied by the DOCTOR. It uses risk management during the design phase to reduce operating risk, and so maximise operating life cycle profits.

<sup>30</sup> Source: Blanchard, B.S., ‘Design and Management to Life Cycle Cost’, Forest Grove, OR, MA Press, 1978.

<sup>31</sup> Barringer, Paul H., ‘Life Cycle Cost & Reliability for Process Equipment’, Barringer and Associates, Humble TX, USA, 1997.



Table 5.2 – Risks Identification Table and Risk Management Plan for a Work Activity Process.

Department	Process	Job	Task	Risks - Possible Causes of Failure	Effects of Worst Likely Failure	DAFT Cost of Worst Failure	Risk Control Plans	Actions to be Taken	Proof that Actions are Completed
Production									
1	Monthly Cost Report								
2		Start Information Collection	Gather Sales information from Accounts	1 Information not available	Report not completed on time	\$500	Warn Accounts of impending report date	Set-up a electronic schedule entry to automatically warn Accounts Manager one week prior report due date	Department Manager to check schedule entered
				2 Wrong information provided	Bad management decision	\$10,000	Get Accounts to double-check cost information is correct	Accounts to include double check actions into their work procedure	Accounts to send copy of revised procedure to Department Secretary for review
				3 Incomplete information presented	Bad management decision	\$10,000	Get Accounts to double-check cost information is complete	Accounts to include double check actions into their work procedure	Accounts to send copy of revised procedure to Department Secretary for review
3		Collate Monthly Costs	Put costs into cost centres						
4		Compile Spreadsheet	Enter cash flow details using data entry procedure						
5		Review Cost Spreadsheet	Department Manager checks spreadsheet						
6			Confirm all costs are recorded						
7		Write Monthly Report	Department Manager writes report						
8			Report forwarded to Head Office						

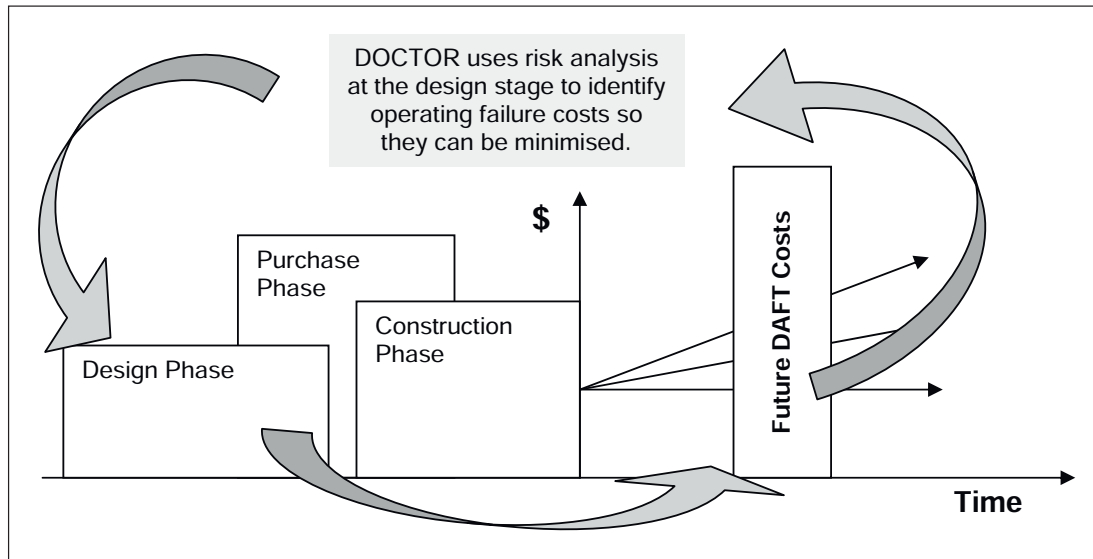


Figure 5.6 – DOCTOR uses Future Operating Costs to Prevent Operating Risks at Design.

DOCTOR applies risk analysis of a design to determine the cost and likelihood of a failure incident during operation. It takes the DAFT Costs incurred from failure and brings them back to the design phase so a designer can make more profitable business decisions and build them into the business' future success. Figure 5.7 shows how to use the DOCTOR during the project design phase.

The DOCTOR rates operating risk while projects are still on the drawing board. If during operation a failure would cause severe business consequences the causes 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 make it more 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 and put into use.

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 estimate of operating and maintenance costs of a project decision realistic. Encouraging the project group to identify real costs of operation during the capital design and equipment selection allows operating profitability to be optimised. Using DAFT Costing in design decisions simulates the operational consequences to good accuracy and the design can be 'tuned' for best life cycle operating results.

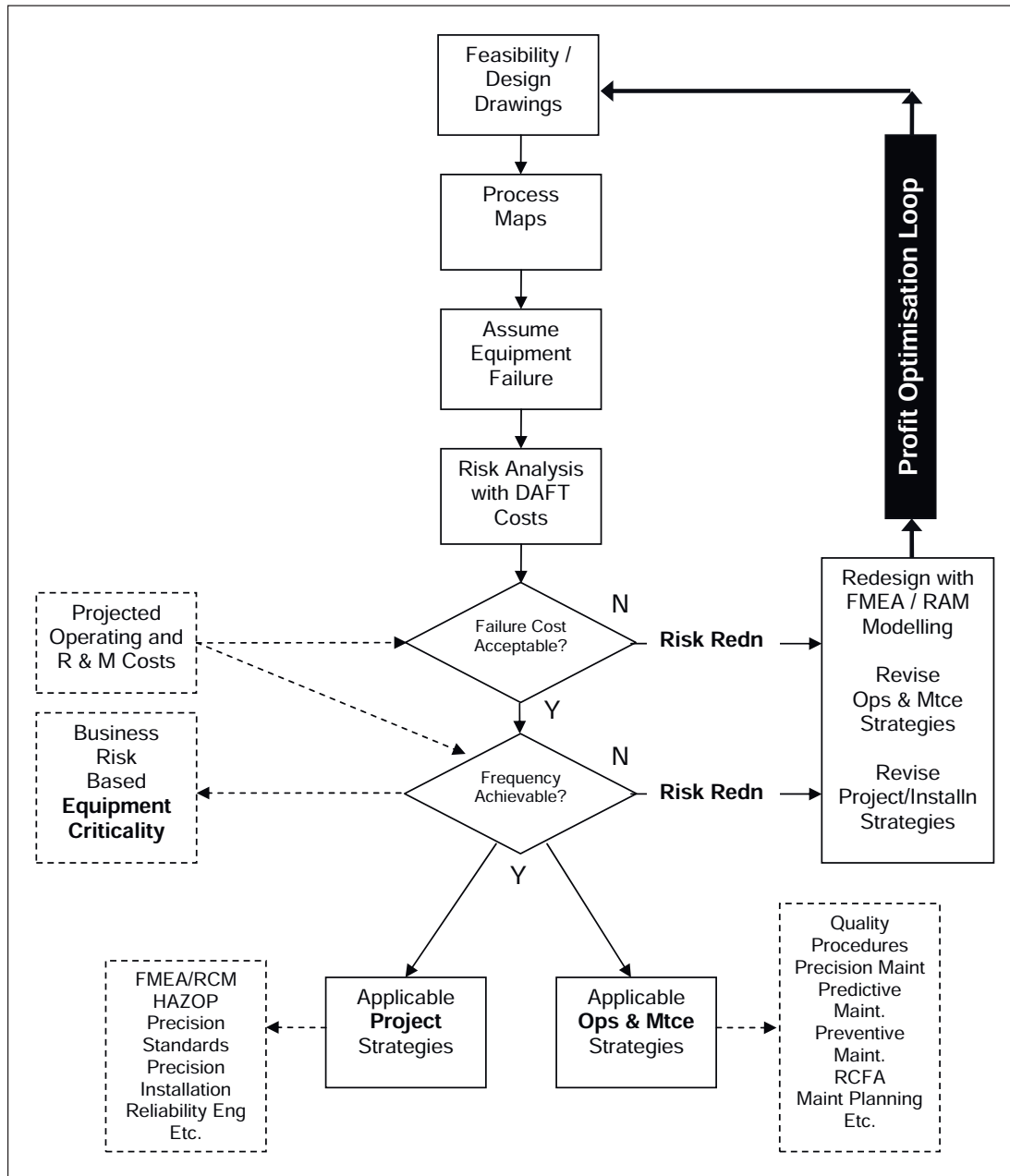


Figure 5.7 – Optimised-Profit Operating Risk Management Design Methodology.

### Controlling Operating Risk during Design

The DOCTOR starts by taking each item of equipment in a project design and assuming it will fail, hence allowing the business-wide impacts of an equipment failure to become clear. Next the consequential DAFT Costs for each assembly on the equipment is identified so parts stock holding can be developed and maintainability improved to allow fast maintenance response for low cost. The financial modelling is done by the project group with computerised spreadsheets identical to those used to analyse the DAFT Costs of a failure incident. The costs and operating assumptions used for costing are the current costs and practices in the organisation using the equipment. The designed-in operating costs of a model are put through review and compared against other choices and their costs. This optimisation process continues until operating costs are minimised.

The DOCTOR process can be applied to every item of plant and equipment, even down to an individual pipe flange or gearbox shaft. The costs of operating failures are used to rate the robustness of the design decision. If the failure costs are unacceptable, then:

- a design change is made to reduce the cost consequence,
- additional risk reduction requirements are included into the design, or
- the operating and maintenance practices are changed to control operating risk and cost.

### Optimising Project and Operating Costs

Each new decision on a design or operating practice is run through the DOCTOR process to compare their operating costs with previous results. If a new choice reduces risk, the expectation is it will lower the operating cost. This iterative way is used to optimise between the least life cycle operating cost and the expense of initial capital cost. Once the operating DAFT Cost for equipment is known a risk analysis is made using a table like that of Table 5.3 to identify those strategies that produce least operating risks. Alternate layouts for more detailed event risk analysis and costing are at your discretion and are available on the CD accompanying this book.

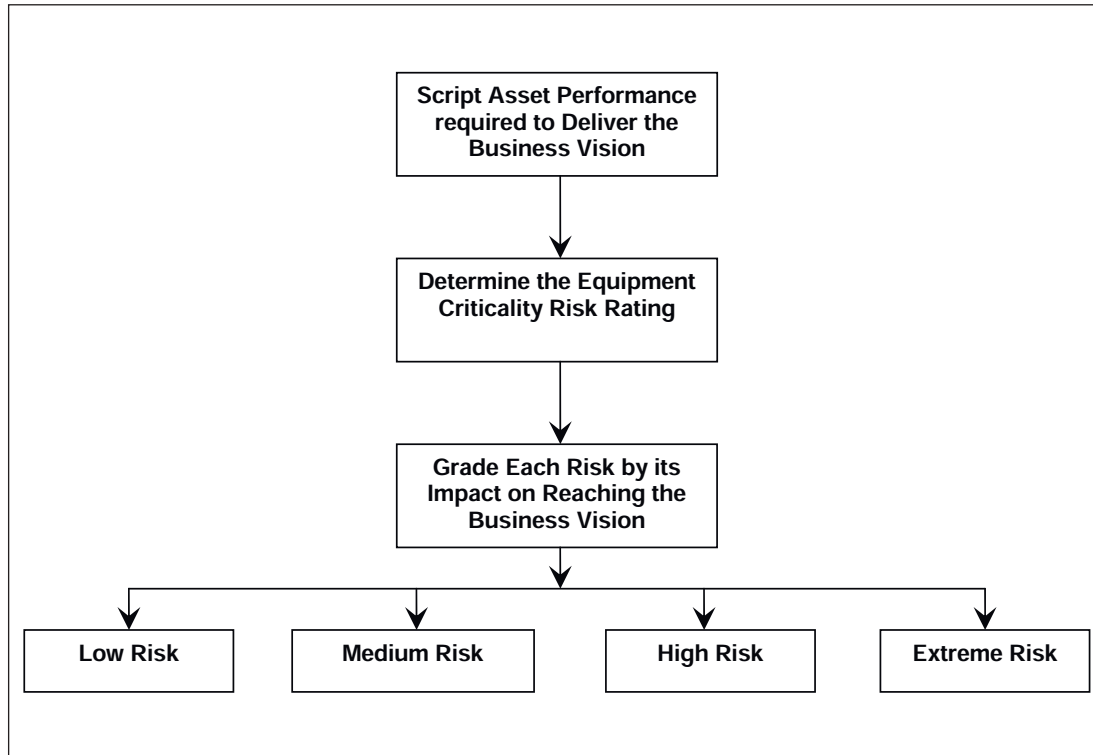
*Table 5.3 – Risks Identification and Management Table for a DOCTOR Risk Analysis.*

Equipment ID No	Equipment Desc	Assembly	Sub-Assy	Parts	Possible Causes of Failure	DAFT Cost of Failure	Risk Control Plans	Actions to be Taken	Proof that Actions are Completed

If least capital expenditure is important (as opposed to least operating cost), the DAFT Cost modelling can optimise for lowest operating costs using least capital expenditure. Alternately, if some other chosen parameter is important, e.g. least environmental costs, or least maintenance cost, etc, the DAFT Cost model lets you optimise them for the least capital cost.

DAFT Costing combined with DOCTOR is a powerful project finance tool to make good business investment decisions. It lets you build future operating scenarios during design. It allows the project group to make sound practical choices and long-term financial judgments on capital equipment selection, project design, and operations and maintenance practices. DOCTOR reduces the chance of poor capital equipment acquisition and destructive long-term financial decisions from not knowing their operating consequences.

## PROCESS 2 – Operating Risk Rating



## **Description of Process 2 – Risk Rating**

### **Script Asset Performance that delivers the Business Vision:**

Before going further with the risk analysis, identify why an asset is in your business and its purpose to the business. Describe in words how each asset benefits the business. Then describe how the asset must perform day after day in order to produce those benefits. Quantify that performance with measurable numbers. Use the process map in which the asset belongs to describe the impact on the operation and the knock-on effects across the business if the asset is not available for service.

For example, a pump used to move product from a vessel to a storage tank must deliver a desired flow at a specific pressure using a motor of sufficient power. The pump must perform its service a certain number of times a day for a certain period at a particular step in the process. This information is important in deciding how critical the equipment is to the business. If the pump cannot do its job, you must know what the impact is to the business. Do this for every item of equipment so its importance is made clear.

Not all assets are equally important and we need to match risk control to the effect the loss of the asset causes the business. The scale of those effects is what the DAFT Costs make clear.

It is also necessary to develop both an Asset Management Policy and a Maintenance Policy. These policies tell why Asset Management and Maintenance are important to the business and give legitimate reason for their existence and for the use of business resources to do them.

### **Determine the Equipment Criticality:**

Equipment Criticality is a measure of the business-wide risk each asset causes a company, and not only to production. To grade the risk requires knowing the cost of the consequences to the business should the risk happen, along with the likelihood that it can happen. The consequential costs of failure are its DAFT Costs. What remains is to estimate the chance that an event will happen.

To quantify chance requires calculating probability of occurrence. This is a difficult requirement unless you trained in probability mathematics and methods. If you have, then calculate the likelihood of each identified failure cause and calculate the risk. If you have not trained in probability and statistics, use a risk matrix. Most organisations use risk matrix ratings to estimate the size of their risks.

### **Grade Each Risk by its Impact on Reaching the Business Vision:**

Recalibrate the risk matrix to the values and consequences of risk your business is willing to carry. You need to know what a low risk, medium risk, high risk and extreme risk is worth in your business. Identify the risk boundary the operation is willing to pay and put into place strategies and actions that limit risk to within the boundary.

Once you determine the risk rating for each failure cause show it in the Equipment Criticality Spreadsheet on the CD accompanying this book.

## 6. Pathway to Plant and Equipment Wellness

The journey to world-class production and maintenance performance starts by charting a sure pathway to get there. It is not accidental to be a world-class operation. First, you chose to become world-class, even when at the start you are not. Then you develop a plan to become good at what you do. Once you reach ‘good’, you develop a plan to become better. At ‘better’, you develop a plan to become the best. When you are the best at what you do, you are world-class. You script the future of your operation with words and diagrams. Like making a movie, where first a script and storyboard is developed, you start with a written script and process maps of exactly how things will happen in your business.

### Enterprise Asset Management

Enterprise Asset Management is a corporate-wide methodology for attaining the physical plant and equipment performance needed to meet business aims. Figure 6.1 is an Enterprise Asset Management process of how to deliver an organisation’s objectives. Enterprise Asset Management is the “systematic and coordinated activities and practices through which an organisation optimally manages its assets, and their associated performance, risks, and expenditures over their lifecycle, for the purpose of achieving its organisational strategic plan”<sup>32</sup>. It derives from the Terotechnology<sup>33</sup> movement in Europe during the late 1980s. The drive for an international asset management specification arose because ISO 9001 did not specifically focus on the performance of physical assets<sup>34</sup>. In fact, had business adopted ISO 9001 as it was designed to be used there would be no need for an asset management specification. Businesses that correctly use ISO 9001 make the necessary businesses system developments to address their plant and equipment performance as part of improving their quality management system.

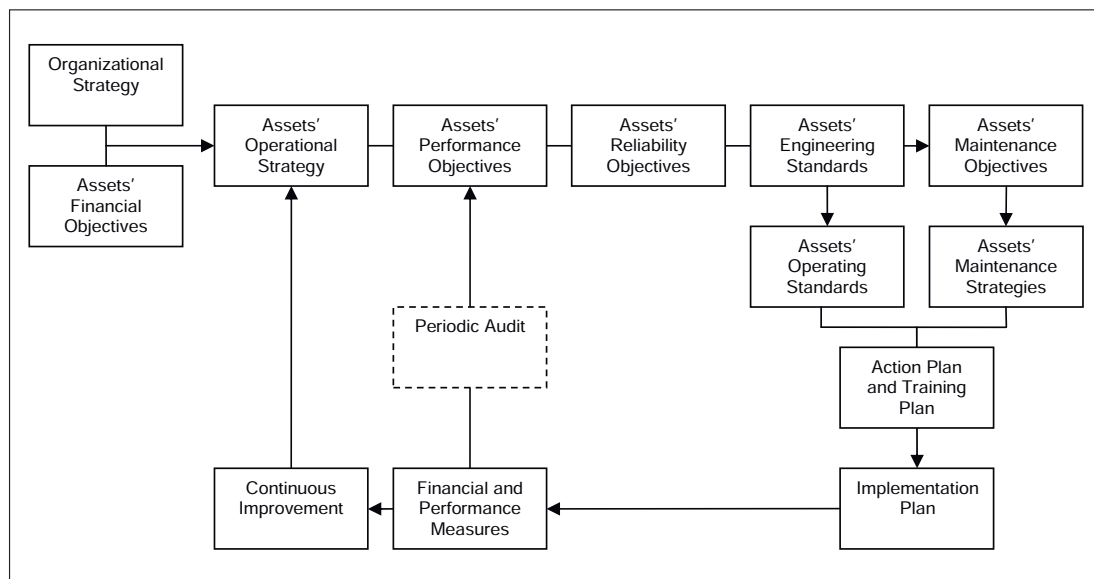


Figure 6.1 – Enterprise Asset Management Model.

<sup>32</sup> PAS 55-1:2004 Asset management. Specification for the optimised management of physical assets, British Standards Institute.

<sup>33</sup> The economic life-cycle management of physical assets.

<sup>34</sup> ISO 9001:2008 Quality Management Systems – Requirements.



The appeal of Enterprise Asset Management is its ‘promise’ of maximum life-cycle profit (LCP), along with its converse, minimum life cycle cost (LCC). But in order to achieve ‘The Promise’ it is necessary to institute the required practices and systems of Enterprise Asset Management throughout the organisation. This is no easy matter in most organisations, especially those that are reactive or those that have become institutionalised over the years. Enterprise Asset Management proposes that businesses follow a path to desired equipment performance by using the foundation elements of systems engineering, reliability engineering, maintenance management, operational management, risk management and industrial engineering, guided by sound financial management. Historically, numerous internationally recognised industrial and the military standards form the documented database of best practices applied in organisations seeking to become world-class engineering asset managers. Practically, the intended achievements of asset management have proven very difficult to attain. The evidence being that extremely few industrial businesses around the world reach the world-class performance level Enterprise Asset Management is meant to deliver. There are important factors not yet recognised by current asset management models and methods that every business needs to deal with themselves. This book aims to provide assistance to industry in addressing the ‘missing links’ needed for enterprise asset management success.

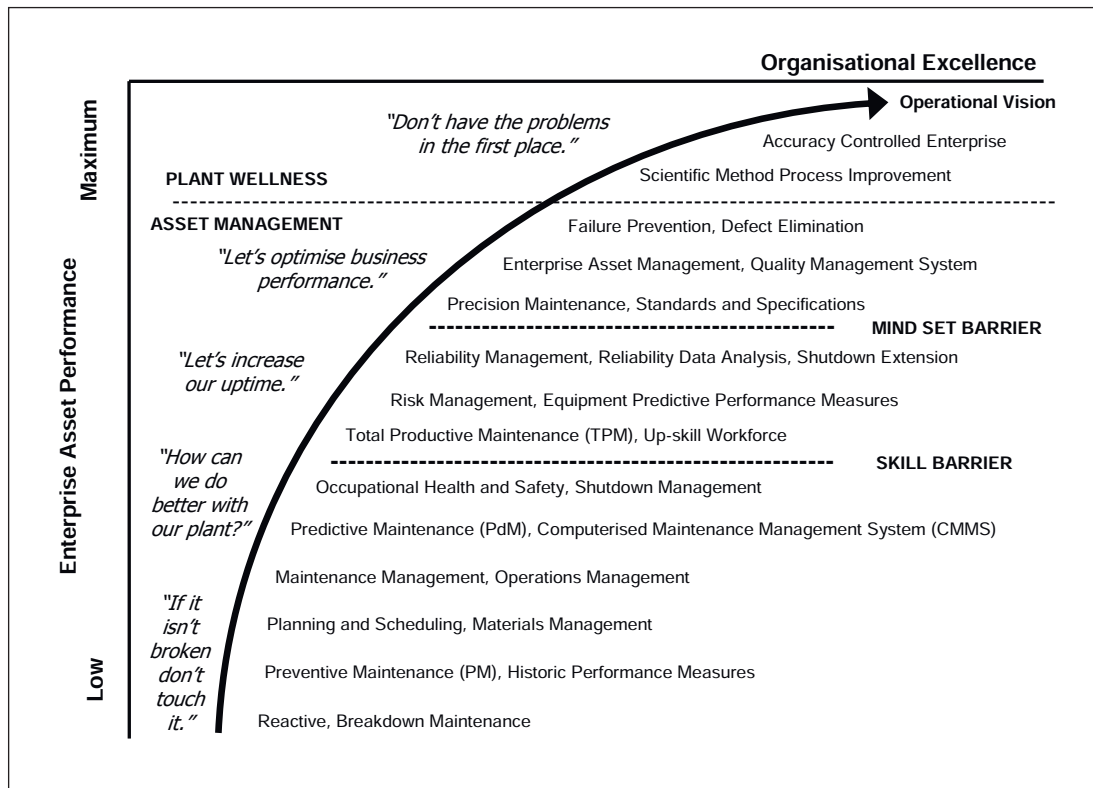


Figure 6.2 – Enterprise Asset Management Pathway with Plant and Equipment Wellness.

The Enterprise Asset Management methodology mix requires time for organisations to introduce them in a staged fashion. In large organisations that have successfully introduced asset management, it has taken up to five years to build the necessary culture and skills<sup>35, 36</sup>. For smaller operations, the time is less. In all cases, committed, stable leadership and change

<sup>35</sup> Flynn, V J, 'Maintenance Benchmarking and the Evolution of DuPont's Corporate Maintenance Leadership Team'. E I Du Pont de Nemours & Co.

<sup>36</sup> Cumerford, Nigel, Crow/AMSAA Reliability Growth Plots And their use in Interpreting Meridian Energy Ltd's, Main Unit Failure Data.

management is required in order to maximise the rate that benefits accrue to an organisation. The changes necessitated by Enterprise Asset Management usually require developing new knowledge and skills in the managers and personnel of the Executive, Finance, Engineering, Operations and Maintenance groups. A representation of the organisational practices and financial controls applied at various stages of a combined Enterprise Asset Management and Plant Wellness initiative is in Figures 6.2 and 6.3.

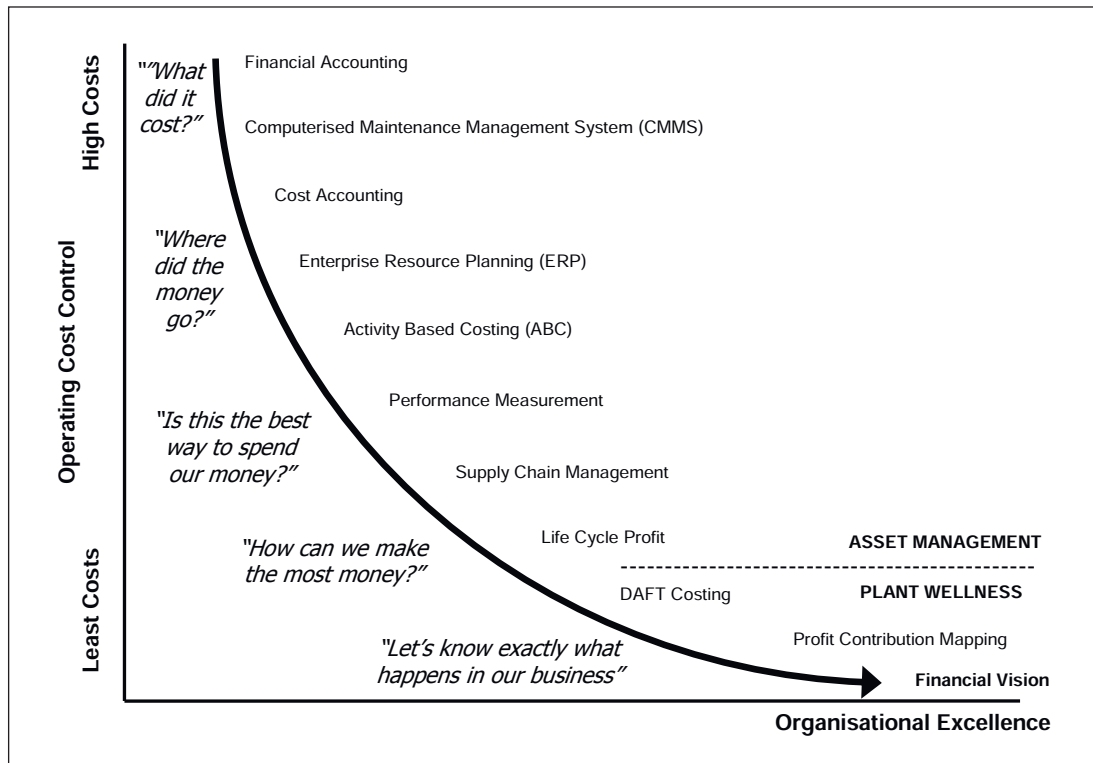


Figure 6.3 – Enterprise Asset Management with Plant and Equipment Wellness Cost Control.

### Introducing Enterprise Asset Management and Equipment Wellness into Organisations

Enterprise Asset Management combined with Plant and Equipment Wellness collect together the key methods for plant and equipment integrity and performance excellence into a life cycle profit philosophy. Plant and Equipment Wellness provides Enterprise Asset Management with additional tools for the selection, use and care of plant and equipment assets to achieve the year-after-year production goals that help deliver the business goals. Plant Wellness helps achieve the desired business results by:

- i. controlling the inherent variability in business, engineering, maintenance and operating processes to within those limits that produce excellence
- ii. managing risk through eliminating the chance of adverse incidents, along with minimising the consequences of a risk
- iii. preventing equipment failure by setting and adhering to high quality standards for parts health throughout their life, starting with sound capital equipment acquisition
- iv. ensuring the accuracy and precision of human intervention and work activity
- v. minimising total life-cycle costs with proactive, fact-based financial modelling of failure, waste and loss

- vi. bringing management and workforce together to work cooperatively as a team of experts building a business that will secure their communal future.

Plant Wellness adds to Enterprise Asset Management the specific need and methods to sustain equipment working parts in perfect health for a lifetime of reliability. It gets management and the workforce working together cooperatively to improve their chance of business success. When you put a critical equipment part at risk of a bad outcome you put the equipment at risk of failure. When the equipment is at risk, the business is at risk. All bad risks become losses when the luck runs out. Those organisations and people that do not give priority to creating parts health and wellness in their operating equipment will struggle to be world-class. They will have too many failures and losses. Production success starts and ends with the individual health and well-being of the parts in your machines. Because when a part fails a machine stops, and then your business starts losing money.

The introduction of change into organisations and the success of a change program requires determined senior management commitment and leadership. The launch of a corporate-wide initiative as large as Plant and Equipment Wellness requires a solid appreciation by senior management of the principles and practices they need to apply if they are to reap the maximum benefits most quickly. To help senior managers grasp the needs and implications of Plant Wellness it is normal that they undergo five-day introductory training in the basic principles, concepts and practices required. With a detailed understanding of Plant and Equipment Wellness senior managers comprehend its impact and effects on the organisation; along with the benefits that result. They can develop a strategy and plan for its introduction. To prevent Plant Wellness from becoming a ‘business fad’ that is quickly dropped if improvements are not swiftly generated, companies undertake its introduction through a ‘pilot program’. A representative portion of the business proves that the concepts and practices deliver improved operating performance and increased profits. Once the ‘pilot program’ is successful it is rolled it out progressively to the rest of the business.

### **Asset Management and Plant Wellness Policy**

An Asset Management and Plant Wellness Policy is used to make sure that business efforts are made to support the wellbeing and long-term health of plant and equipment. The policy drives the engineering, projects, production, maintenance and finance groups to improve equipment part health and wellness. A successful business needs plant and equipment that makes on-time, low-cost, quality product customers willingly buy. Because an industrial operation’s future depends on their equipment working accurately and reliably, the finance, engineering, operations and maintenance groups need to protect and improve the wellness of their machine’s parts so they get high reliability and a trouble-free operating plant for their business.

It is important to ensure that an asset wellness policy meets all the requirements that make it a useful and valuable document for guiding plans and practices. A policy needs to be inspirational to the people it applies to. A policy needs to excite those people and get them out of bed each day motivated with positive expectation. A limp policy does nothing for its readers or the company. The final published policy may need to be written by a writer who can inject that sort of energy and life into it. Table 6.1, Asset Policy Content Comparison Table, is intended to help build into the asset management and wellness policy those things that are important in minimising risk and maximising plant and equipment health and wellness. It lists the quality, risk and asset management policy requirements of internationally recognised standards.

That does not mean an asset management policy must comply with every requirement in the table. The most important factor must be the amount of ‘life’ the policy breathes into the people and the business, along with its ability to produce good equipment parts’ health decisions and actions. But the checklist will help to get useful content into the policy so that it

focuses business efforts on the right things – those that actually reduce life-cycle operational risk. An example of an Asset Management and Equipment Wellness Policy might be:

*“We recognise that our plant and equipment are the foundation on which our livelihoods, plans and dreams depend (Shareholders, Staff, Employees, Suppliers, Customers and Community). Without sure and certain, competitively-priced, quality products from our operation, we put our collective and individual futures at grave risk.*

*Because our business and personal success depends on the reliable and faithful production of 100% quality product that satisfy our customers’ requirements, we will adopt and use those proactive asset management, engineering, project, operational, maintenance and financial practices, methods and business systems that minimise operating risks and prevent failure of our plant and equipment during its operating lifetime.*

*Starting from the conception of a business idea through to the decommissioning of a plant we will work together in cross-functional teams to seek ways that maximise the safety, productivity and value-added in every part of our operation, and its supply and distribution chains. Included is the need to constantly minimise, and eventually eliminate, our business losses, wastes, accidents and incidents so that we do no harm to our planet, our people and our community.*

*We want all our people to continually seek and learn better ways that improve our productivity and minimise our risks in every task. We encourage their learning with both formal methods and by controlled experimentation. Through the on-going drive of our people to seek excellence and mastery, we will become and remain a best-in-class performer.”*

A shorter asset management and equipment wellness policy example is:

*“We support a well-planned and executed Asset Management and Plant Wellness strategy encompassing best operations and maintenance practices as a key risk management tool to assure plant performance, and positively contribute to the achievement of our business outcomes.*

*Maintenance is fundamental to successful production, and the reliability of our plant and equipment assets is dependent on doing the maintenance function effectively, in a timely manner.*

*We recognise that successful equipment performance is due to the cooperative contributions of its maintenance, operations, engineering and finance departments and to an operational culture of relentless risk management, responsible and controlled business risk taking, defect prevention and failure removal, continuous improvement and cross-functional staff involvement in decisions.”*

## **Maintenance Vision, Policy and Maintenance Strategy**

Part of developing a maintenance strategy is to first develop a maintenance policy – what to achieve with equipment maintenance, why it is necessary for the business, and how to do it. With the importance of maintenance to production success firmly placed into a business context through the Asset Management and Equipment Wellness Policy, it becomes necessary to decide how to use maintenance to maximise production productivity. This is the role of the Equipment Maintenance Policy and Strategy. The maintenance policy explains how to use plant and equipment maintenance to ensure the necessary production performance from the plant and equipment.

Table 6.2 is a tool to help identify the maintenance vision and policy. Plot where the operation is in each column and then decide where you want to go over the next 2 to 3 years. Plotting on the chart helps the development of a maintenance vision to guide the drafting of the policy. With the policy decided then work can start on the strategy and actions, which when achieved will get the vision.

Listed below are the typical issues to address in a maintenance strategy document. There may be others specific to your operation. Its development is a substantial undertaking. But

without it maintenance flies-by-the-seat-of-their-pants, everything becomes guess-work and the business is run by luck rather than good management. Without maintenance policy and strategy vast amounts of production time and money are wasted. With maintenance policy and strategy there is a far better chance of becoming a great company. Turning a company into a world-class leader is a job worth doing well.

## **Typical Contents of an Equipment Maintenance Strategy Document**

**Maintenance Vision** (Why you do maintenance and how it helps the business)

**Maintenance Policy** (How your business does maintenance, who does it, what you expect from it)

**Production Performance Envelope** (what daily plant availability meets the production output? What is the daily average production rate to sustain that delivers the required output? What is the daily quality rate required to meet production plans? What is the equipment reliability needed for each piece of plant to deliver the total plant availability required to meet the production plan? How much can you afford to spend on maintenance and repairs?)

- Production Performance Required
- Process Reliability Analysis (reliability model your production process to identify its weaknesses and most likely performance)

**Risk Assessment of Operational Assets** (what can go wrong with your equipment, what will it cost, how often does it happen. The equation is: Risk = cost consequence [\$] x no. of events in a period [/yr] x chance of event ('chance of event' is between 1, if it will definitely happen, to 0, if it definitely will never happen). This is done in a spreadsheet using the DAFT Costs as the consequences value.)

- Equipment Level (e.g. a complete pump-set)
- Financial and throughput impact on Production of failures on each equipment item
- Equipment Criticality (prioritise the importance of the equipment to sustaining production)
- Assembly Level (e.g. pump – coupling – motor – base frame – foundations – power supply)
- Failure Mode and Effects Analysis at part level (identify the parts in the assemblies that can fail and in which ways. Then identify the operating practices and maintenance each part requires to prevent production failure.)

**Production Risk Management Plan** (how maintenance is used at the parts and assembly level to reduce production risk at the equipment level)

Precision Maintenance Standards needed to meet plant and equipment operational performance (Mechanical, Electrical, Instrumentation, Structural, Civil – Safety, Environmental, etc)

List Equipment on Preventive Maintenance (make adjustments and/or replace wearing parts)

- List of equipment done as shutdown, or as opportunity-based PMs, or as time/usage scheduled PMs
- Precision standards to meet when performing PMs

List Equipment on Predictive Maintenance (to detect impending failure and repair/replace before failure)

- What condition monitoring will be used
- Where will the condition monitoring be done
- How will it be decided when it is time to maintain or replace
- Who will do the condition monitoring (i.e. subcontract, in-house maintainer, in-house operator)
- What will be done when condition is too far deteriorated

List Equipment to Rebuild (to identify which equipment to repair)

- Criteria to pass to justify repair instead of replacement
- How many times to rebuild before replacing with new
- Precision standards to meet on each rebuild
- Precision standards to meet on re-installation

List Equipment to Replace (identify which equipment is not to be repaired, but always replaced. The DAFT Cost of a breakdown often easily justifies installing new equipment, rather than take the chance of an unplanned production stoppage)

- Precision standards new equipment must meet
- Precision standards to meet on installation

Critical Spares List (to identify which parts you must have available)

- Equipment parts to be carried on-site
- Equipment parts to be carried by local supplier
- Stores management standards to protect integrity of spares

**Records Management** (to document maintenance history of equipment and parts usage in order to identify reliability improvement opportunities)

- Which engineering, operational and maintenance documents to keep
- How documents are to be kept current and safe
- What records are to be made and kept over each equipment life
- What analysis of records will be required and the information to be provided from the analysis
- How will all the records and documents be controlled

**Maintenance Performance Monitoring** (to ensure that maintenance is delivering the reliability, availability, quality and cost that the production plan requires)

- KPI definitions and calculations
- Plant level KPIs (e.g. availability, unit cost of production, quality rate)
- Equipment level KPIs (e.g. reliability, quality rate, production rate)



- Personnel KPIs (e.g. hours spent developing skills, employee satisfaction)
- Maintenance Process Performance KPIs (e.g. daily work order complete per trade type, backlog of work, percent planned work, percent scheduled achievement)
- Maintenance Improvement KPIs (e.g. no. of procedures written to ACE 3T standard, no. of design-out projects started, no. of design-out projects completed)
- Reliability Prediction KPIs (e.g. no. of work orders spent improving reliability, reliability improvement graphs e.g. Crow-AMSAA plots)

**Maintenance Resources Required** (there will be a need to resource the production risk management activities known as ‘maintenance’)

- Necessary maintenance equipment and technologies
- Necessary stores capacity and stores internal operating methodologies
- Necessary engineering and maintenance knowledge
- Necessary trade skills and competence
- Necessary numbers of people by trade type/service
- Location of people for most efficient operation of maintenance activities
- Necessary Computerised Maintenance Management System (CMMS) capabilities

**Cost and Benefit Analysis** (to confirm that the cost of doing maintenance will return value to the business)

- Annual maintenance cost verses the cost of failures prevented (the risk analysis will provide the DAFT Costs that will be incurred by the business if equipment fails)
- Annual maintenance cost verses the cost of lost production output if plant availability does not meet production targets (your production and equipment history can be used to determine the numbers of production slowdowns and stoppages in an ‘average’ year that did not need to happen)

**Rolling Two Year Maintenance Program** (indicate exactly when and what is to be done with each item of plant to deliver maximum production productivity)

- Work orders by type performed on each equipment item and the benefits they provide
- Schedule of work orders for each equipment

**Rolling Two Year Maintenance Budget** (develop a believable budget that will deliver the risk control that production needs. Using a rolling two years forecast allows inclusion of the savings from improvement initiatives. Two years is a believable period for anticipating changes. A five years forecast becomes unrealistic in the later years because it cannot anticipate the impacts of a changing world.)

- |                                 |                                    |
|---------------------------------|------------------------------------|
| • Maintenance cost by equipment | • Maintenance cost per time period |
| • Maintenance cost by plant     | • Equipment improvement plans      |
| • Maintenance cost by type      |                                    |



**Rolling Five Year Reliability Improvement Plan** (the on-going list of scheduled activities, funds and resources that will be committed to continually improve the operation. The focus is on activities that improve equipment reliability)

The list is reasonably comprehensive but may need to be tailored to suit the situation and the requirements of a business and its management. Once the time and effort is put into developing such a detailed strategy there will be confidence that it can achieve its intention. Such a document is the result of many peoples' efforts and input. A team consisting of production, engineering, maintenance and finance working together is the best way to develop it. It can take three to six months to do the job fully. But a simpler document can be compiled within a couple of months and later refined as resources become available.

Table 6.1 – *Asset Management Policy Content Comparison.*

<b>Policy Requirements</b>	<b>Quality Management System ISO 9001:2008</b> Top Management (Board or Chief Executive Officer)	<b>Physical Asset Management System PAS55-1:2004</b> Top Management	<b>Risk Management System AS4360:2004</b> Board or Executive
Responsible to develop policy	<ul style="list-style-type: none"> <li>Commitment to comply with requirements of the Quality Management System</li> <li>Commitment to continually improve effectiveness of Quality Management System</li> </ul>	<ul style="list-style-type: none"> <li>The overall physical asset management objectives</li> <li>That physical asset management is directed at achieving the Organisation's strategic plan</li> <li>A commitment to continually improve the physical asset management process</li> <li>A commitment to comply with current applicable legislation, regulatory and statutory requirements and with other requirements subscribed to by the Organisation</li> </ul>	
Obligatory policy content inclusion			
Recommended policy content inclusions			<ul style="list-style-type: none"> <li>Objectives of risk management</li> <li>A commitment to risk management</li> </ul>
Possible policy content inclusions			<ul style="list-style-type: none"> <li>Objectives and rational for managing risk</li> <li>Links between policy and strategic/corporate plans</li> <li>Guidance on extent and type of acceptable risks taken and ways to balance threats and opportunities</li> <li>Processes to be used to manage risk</li> <li>Accountabilities for managing particular risks</li> <li>Details of support and expertise available to assist those accountable for managing risk</li> <li>Level of documentation required</li> <li>Statement of how risk management performance will be measured</li> <li>Commitment to periodic review of risk management system</li> <li>Statement of commitment to the policy by directors and executives</li> <li>Create linkages to other corporate strategies</li> </ul>
Organisational context	<ul style="list-style-type: none"> <li>Appropriate to the purpose of the Organisation</li> <li>Equal and consistent to Organisation's overall policies and strategy</li> <li>Provides the framework for setting and reviewing measurable quality objectives</li> </ul>	<ul style="list-style-type: none"> <li>Appropriate to nature and scale of Organisation's physical assets and operations</li> <li>Be derived from how the management of physical assets will help achieve Organisation's strategic plan</li> <li>Consistent with other Organisational policies</li> <li>Provides the framework for setting physical asset management strategy, objectives, targets and plans</li> <li>Be consistent with Organisation's risk management framework</li> </ul>	
Showing commitment to policy	<ul style="list-style-type: none"> <li>Visibly endorsed by Top Management</li> <li>Communicated across organisation</li> <li>Understood by all persons within organisation</li> <li>Reviewed for continuing suitability</li> </ul>	<ul style="list-style-type: none"> <li>Visibly endorsed by Top Management</li> <li>Documented in suitable media</li> <li>Implemented into use to be standard practice</li> <li>Maintained in condition to meet purpose</li> <li>Communicate individual physical asset management obligations               <ul style="list-style-type: none"> <li>To relevant employees</li> <li>To relevant third-parties</li> </ul> </li> <li>Published to stakeholders where appropriate</li> <li>Reviewed periodically for relevance and consistency to Organisation's strategic plan</li> </ul>	<ul style="list-style-type: none"> <li>Publish Policy</li> <li>Establish management team to communicate and involve staff across organisation               <ul style="list-style-type: none"> <li>Raise awareness across organisation on risk management process</li> <li>Risk management is in the organisation's culture</li> </ul> </li> </ul>

Table 6.2 – The Journey to Reliability and Maintenance Mastery.

	Leadership and Capability						Systems and Processes			
	Maintenance Vision & Strategy	Performance Measures	Organisation Structure	Human Resources	Knowledge Base	Maintenance Strategy	Materials Management	Planning & Scheduling	Contractor Management	Reliability Engineering
<b>Mastery</b>	Quality System managed Accuracy Controlled Enterprise where everyone in every department works to 3T error prevention procedures; Lean philosophies improve processes	Business strategy focus; Maximising Life Cycle Profit; Defect And Failure True (DAFT) Cost database, Process Step Contribution monitoring across all processes	Integrated cross- functional teams incorporating financial, engineering, operations and maintenance	Empowered, flexible, cross- functional teams of experts working to scientific discipline	Continually learning, pushing-out the boundaries of human knowledge and understanding. Six Sigma discipline is normal	Precision Domain drives all engineering, installation, operations and maintenance work; Risk analysis and management normal	Materials problems designed-out; OEM monitors real-time information on critical parts' condition and carries necessary spares	Maintenance reducing as continual improvements extend time between outages; continually reducing time to repair with Lean philosophies	Small teams of experts servicing entire local industry delivering precision maintenance and design-out maintenance with profit sharing	'Design and Operations Cost Total Optimized of Risk' (DOCTOR) is used to minimise all operating risks throughout the facility's life. Reliability growth permeates thinking
<b>Excellence</b>	Personnel action plans; appraisals are clearly tied to the maintenance strategy	On-going benchmarking of metrics and processes; Full cost database	Total Productive Maintenance where operators drive reliability, fault-find and maintain equipment; root cause failure analysis by operators and maintainers	Empowered, flexible, world- class workers; self-managed teams	Expert systems used; fully integrated CMMS common database	Preventive & Predictive plans continuously optimized; the 'right' maintenance tactic is applied based on analysis	Stores system integrated to CMMS and accounting system; bar coding or radio frequency tags of all stores items; World- class Stores Management	>90% all maintenance is planned and >95% first-time schedule compliance; rolling schedule fixed for the week ahead	Small numbers of contractors on long term sharing partnership agreements with high innovativeness	Risk and unplanned failure reduced to best in industry by analysis and modelling
<b>Competence</b>	Reliability focused Maintenance improvement action plan is linked to the maintenance Management Strategy	Statistical process control applied to maintenance process measures; Equipment specific maintenance costs available	Established teams for achieving key objectives in the Maintenance Management Strategy	Multi-skilled trades with process capability analysis and basic operating skills	Easy access to knowledge bases available to all employees at all times	Preventive & Predictive plans exist for all maintainable items; emphasis on PdM. All tactics understood	Single source supplier partnerships established and effective; Area stores with visual controls; Reliability of spares maintained; Suppliers provide technical expertise	Long term asset planning established; Critical path analysis used for all rebuilds and shutdowns	Contractors are established based on principle of 'risk sharing'; Contractors provide technical expertise	Effective Root Cause Analysis (RCA) applied to equipment problems to extend life
<b>Understanding</b>	A clear Maintenance vision and strategy is documented and communicated to all employees	Input – Output process measures reviewed and displayed; Downtime by cause; Segregated maintenance costs reviewed	Decentralized with central support; Clearly written, mandates/roles for each maintenance function and group	Trades have problem identification and solving; team dynamics and training skills	Document control system established; CMMS installed and used to manage knowledge bases	Preventive & Predictive plans exist for key equipment; Compliance to scheduled plan is more than 95%	Spares classified with separate strategies; Spares linked to BOMs/Equipment Drawings; Standardisation policies exist; ABC spares management with 'A' spares protected	All but unexpected failures planned; All planned jobs specify safety, labour, materials, tools, technical details	All contractors repairing rotables are capable of Original Equipment Manufacturer's testing	Basic equipment conditions established; Good failure databases; All major failures investigated; PvMs modified based on site experience
<b>Awareness</b>	No clearly documented role of maintenance; No Maintenance vision or strategy	Some downtime records; Maintenance costs regularly available, but not segregated into area/line	Centralized maintenance group with alignment to production; Team approach to technical problems	Trades have OH&S and maintenance support (inspection, reporting) skills	Plant register established and useful data collected; central technical library; All drawings and equipment information identified	System to identify all maintainable items exists; Emphasis on time- based overhauls and inspections	Stores catalogue established; Inventory accuracy >95%; Goods receiving practices in- place	Work Request/Work Order system established; Major rebuilds, shutdowns fully planned and programmed	Contractors used for core maintenance work	Collect the failure data; Equipment histories occasionally reviewed for failure analysis
<b>Innocence</b>	The main role is to fix it when it breaks/fails	Incomplete or no maintenance downtime records; Maintenance costs not readily available	Centralized maintenance group with no alignment to production; Command and Control' approach	Trades have their basic trade skills, however little or no technical knowledge or support and training given	Ad-hoc records kept for purchasing; No plant register or control of drawings	"If it isn't broke, don't fix it"; Annual shutdown and inspections only	Ad-hoc stores; No costing or control of spares	No planning function; planning done on-the-run; Short term focus	All maintenance carried out by in- house team, which may include individual contractors	No failure records

## 7. Defect Elimination and Failure Prevention

The following extracts are from three sources investigating industrial plant and equipment failures.

“Many managers and engineers believe most failures have a root cause in the equipment <sup>37</sup>. Data from nuclear power plants (which maintain a culture of confessing failures and the roots of failures – this is in opposition to most industries where the culture is to hide the roots of failures) show the following roots for failures:

### Early in the life of nuclear power plants –

Design error	35%	[people induced problems, not calculation errors]
Random component failures	18%	[process/procedure problems]
Operator error	12%	[people/procedure problems]
Maintenance error	12%	[people/procedure problems]
Unknown	12%	
Procedure error & (procedure) unknowns	10%	
Fabrication error	1%	[people/procedure problems]
	<u>100%</u>	

### Mature nuclear power plants –

People	38%
Procedures & Processes	34%
Equipment	28%
	<u>100%</u>

“ASME (2002 report) shows a similar root for failures. For 10 years, from 1992-2001, 127 people died from boiler and pressure vessel accidents and 720 people were injured. In the 23,338 accident reports, 83% were a direct result of human oversight or lack of knowledge. The same reasons were listed for 69% of the injuries and 60% of recorded deaths. Data shows that if you concentrate only on the equipment you miss the best opportunities for making improvements. Another point to seriously consider is little or no capital expenditures are required for improving people, procedures and processes which can reduce failures. In case you believe that equipment is the biggest root of problems it will be instructive to download (<http://www.bpresponse.com>) the Final Report of BP's Texas City Refinery explosion and tick off the reasons behind the explosion which took the lives of 15 people and maimed more than 200 additional people—you will see objective evidence for people, procedures and processes as the major roots for failures. The #1 problem was not equipment! <sup>38</sup>”

“... the major challenge to reliability theory was recognised when the theoretical probabilities of failure were compared with actual rates of failure [and the] actual rates exceed the theoretical values by a factor of 10 or 100 or even more. They identified the main reason for the discrepancy to be that the theory of reliability employed did not consider the effect of human error ... Human error in anticipating failure continues to be the single most important factor in keeping the reliability of engineering designs from achieving the theoretically high

<sup>37</sup> Barringer, H. Paul, P.E. ‘Use Crow-AMSAA Reliability Growth Plots To Forecast Future System Failures’, [www.barringer1.com](http://www.barringer1.com).

<sup>38</sup> Barringer, H. Paul, P.E. ‘Use Crow-AMSAA Reliability Growth Plots To Forecast Future System Failures’, [www.barringer1.com](http://www.barringer1.com).

levels made possible by modern methods of analysis and materials ... nine out of ten recent failures [in dams] occurred not because of inadequacies in the state of the art, but because of oversights that could and should have been avoided ... the problems are essentially non-quantitative and the solutions are essentially non-numerical. <sup>39</sup>”

The above quotes are evidence that the problems we have with our plant and equipment are not machine problems. Our machines are fine. The problems of poor equipment reliability, poor maintenance and poor production performance are in the minds and hearts of the people that control our companies, design and manage our business processes, and run and maintain our machines. The reason companies have so many equipment and production failures is that their people and business processes cause them. That is the conclusion from the evidence in the three extracts. Human beings let happen all equipment failures that are not ‘Acts of God’. If you want to make serious improvements to your plant and equipment reliability you need to first focus all your efforts and resources on changing attitudes and beliefs. You need to change the way people think about, and value, quality and reliability.

Remember always the famous advice of quality guru, the late W. Edwards Deming, “Your system is perfectly design to give you the results that you get!” His quote truthfully explains why you get the results that you do; you designed them into your business systems because you neglected to design them out! If you don’t want reliable equipment, simply don’t tell your operators and maintainers how to deliver reliability. The ‘human factor’ will make sure you get a matching level of equipment performance. To move from a repair-focused organisation, where failure is seen as inevitable, where maintenance is a servant to failure and reliability is the responsibility of an ‘elite’, to a reliability-focused organisation with a culture of failure elimination that permeates staff at all levels, requires a mindset change. It is driven by a passionate management over a long time <sup>40</sup>.

You start changing to a reliability culture by first installing the right processes and systems into your business. Then you teach the people to follow them. Read this quote about causing change in organisations – “Changing collective values of adult people in an intended direction is extremely difficult, if not impossible. Values do change, but not according to someone’s master plan. Collective practices, however, depend on organisational characteristics like structures and systems, and can be influenced in more or less predictable ways by changing these. <sup>41</sup>”

You cannot change people’s internal values, but what you can change is the practices they must follow so that their cognitive dissonance brings about change in their values. Cognitive dissonance is the uncertainty and unhappiness that happens in your mind if you believe one thing, but are forced to do something else. For example, if you want people to do high quality work, provide a high quality procedure that they must follow along with a report sheet to complete and hand-up at the end of every job, so that you can encourage and train them to do masterly work. If, when the procedures are exactly followed users produce better results than they ever achieved without them, they will start to change their belief. Their old internal values change because the external evidence does not support them. This is cognitive dissonance in action. In this way the quality requirements built into the procedures brings about the necessary change in the value people put-on careful observation, quality workmanship and accurate recording. You use your standard operating procedures to describe and create the ‘role model’ you want your people to follow.

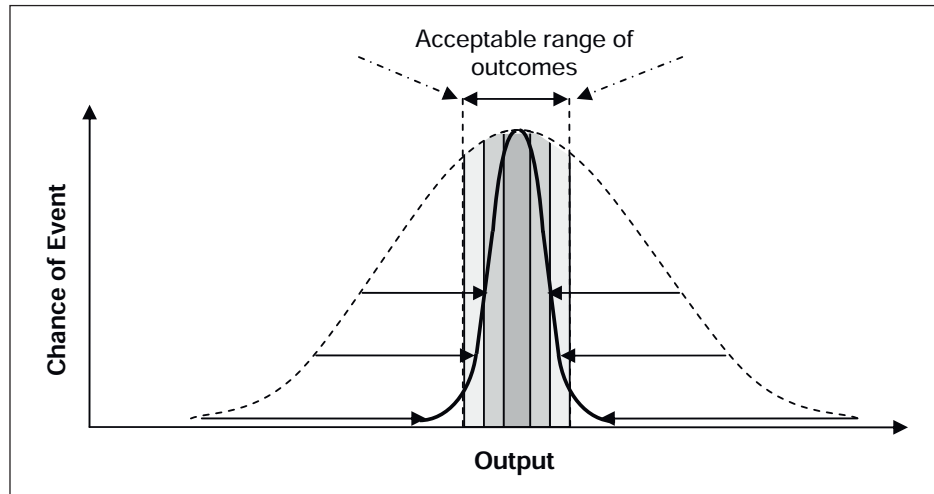
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<sup>39</sup> Petroski, Henry, ‘Design Paradigms: Case Histories of Error and Judgment in Engineering’, Cambridge Press, New York, 1994. Remarks on Pages 7 and 8 about the role of humans in failures.

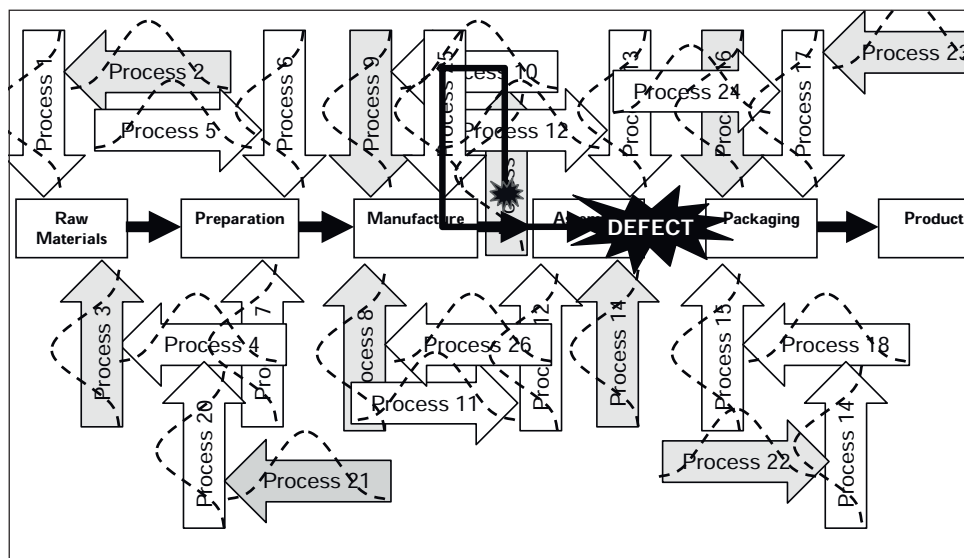
<sup>40</sup> Wardhaugh, Jim. Extract from 2004 Singapore IQPC Reliability and Maintenance Congress presentation ‘Maintenance – the best practices’.

<sup>41</sup> Hofstede, G. J., Cultures and Organisations – Software of the Mind, Second Edition, McGraw-Hill.

Unwanted variation causes defects and failure is the message in Chapter 3. The challenge for a business is to control variation to within those limits that produce good outcomes. If too many of its outputs are unacceptable a process produces excessive losses. Such a situation is terribly wasteful and needs to be investigated to understand the causes of the problems. A successful resolution will alter the output spread so that all products are within the specification. The output spread will change from a volatile distribution to one more stable, as shown in Figure 7.1. Now the vast majority of process output meets specification.



*Figure 7.1 – The Effect of Removing Volatility from Processes.*



*Figure 7.2 – Processes which Allow Wide Variation Produce many Defects.*

A business with poor process controls provides many chances for producing scrap and waste. Having poor controls causes continual opportunities for unwanted variations to arise and encourages great loss by not preventing their transmission through the business. Figure 7.2 indicates that each process in a business produces variable outcomes which feed into downstream business processes. Any quality problem created in a process travels through the business to eventually become a defect that has to be rejected in another process. Once rejected, all the work, money and time spent on it is wasted. The business loses money and customers get annoyed.

## The Need and Purpose of Standardisation

In his books, the late was concerned about the impacts of variability on business because he knew from industrial experience that it caused great waste, inefficiency and loss. Starting in 1950 he taught industrial statistics to the Japanese. Including the use of process control charts to identify changes in processes so that corrections could be made before product quality deteriorated out-of-control. The Japanese managers, engineers and supervisors learned well and by the 1960s Japanese product quality was renowned world-wide. The Japanese were gracious and willing told the world what they had learned. During trade visits to high-quality Japanese companies the Japanese hosts explained to visitors the factors they believed had made the greatest difference <sup>42</sup>. One factor in particular was regularly identified as the most important to start with. It was to standardise a process so that there was one way, and only one way, that it was done.

What had the Japanese learnt about variation that western business managers have not? The Japanese saw that output variation was either the natural result of using a particular process (called common cause variation because it was inherent, common, to a process) or caused by factors external of the process changing its performance (special cause variation because they were identifiable as a particular problem special to a situation). They also noticed that the extent of the output spread was dependent on the amount of volatility permitted in a process. If many methods of work were allowed, each introduced its own effects. Each new method caused the final process output to be slightly different to that of the other methods. But when one standard method was used the outputs were less variable. The difference in output distribution between a standardised method and the use of any method is shown in Figure 7.3. Standardisation reduced variation. Once a method is standardised the use of any other method is an external special cause factor, easily identified and corrected by training if it produces volatility, and gladly accepted into standardised practice if it reduces volatility.

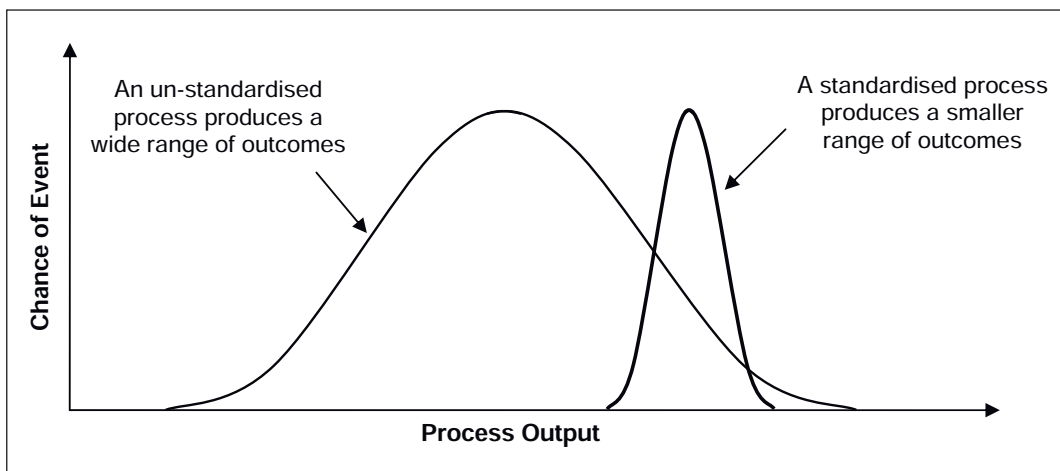
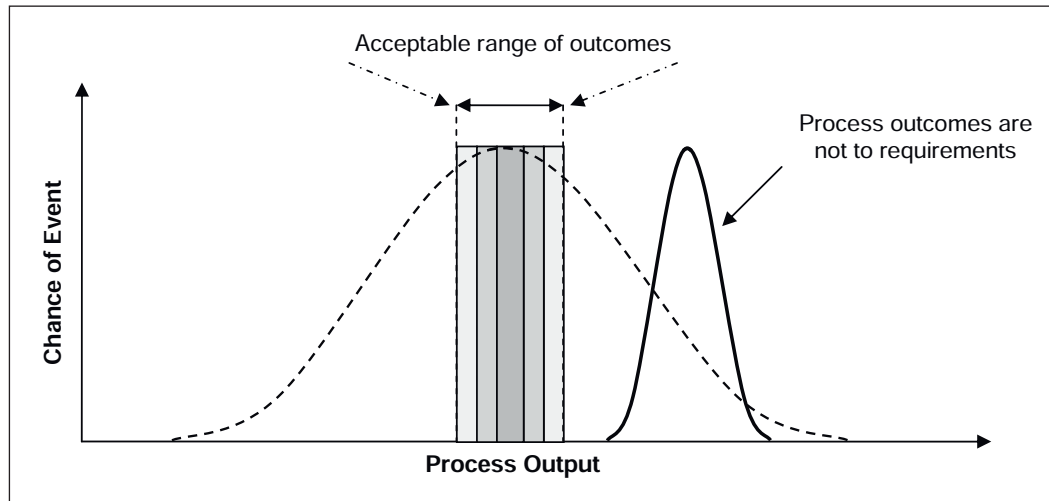


Figure 7.3 – The Effect of Applying Standardisation on Process Results.

However, standardising did not ensure that it was the best method for achieving the requirements. In Figure 7.4 the process produces fewer variations, but its output is not to specification.

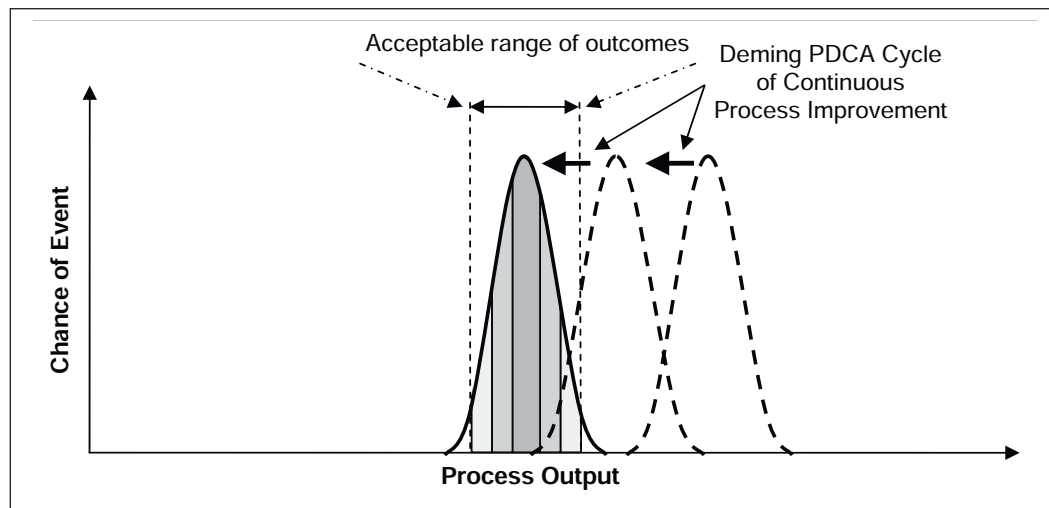
<sup>42</sup> Bodek, Norman., 'Kaikaku – the Power and Magic of Lean – A Study of Knowledge Transfer, PCS Press, 2004.





*Figure 7.4 – Low Variation but Output is not to Specification.*

In such cases the Japanese repetitively applied the Deming Cycle (Plan-Do-Check-Act) to trail new methods and learn which produced better results. Through experimentation, testing and learning they continually improved a process until the outputs met the requirements. The approach used by the Japanese to build high-quality processes is shown in Figure 7.5.



*Figure 7.5 – Altering Process Performance to get Desired Results.*

### **How to Use This Knowledge in Your Business**

The Japanese learnt that they could change their business processes to produce the results they wanted. It did not matter how much variation existed because if it was due to the process they changed and improved the process. If variation was due to external special causes they found and removed them. Figure 7.6 reflects what to do to create a process with excellent outcomes, no matter where you start.

First identify what is excellent performance and set the limits on its allowable variation. If the current process cannot deliver the required results; redesign it and standardise on one way, and one way only, for the process to be done. Use process control charts to monitor the

process and its variables. The process control charts help to find those special causes that prevent excellence and remove them. Make the changes and run the new process. If the new standardised process does not meet requirements after all special causes are removed, the process is not capable of doing so. Because it is a process problem preventing achievement, the process needs to be redesigned and changed to one that can deliver the necessary quality. With each running of the process a great deal of learning is gained. This learning is used to decide how to change the process to deliver improved performance. The process is again modified and run. This 'scientific method' of process development and improvement is repeated until the process produces the required quality results. This is how the Japanese moved their businesses up to world-class quality and cost performance.

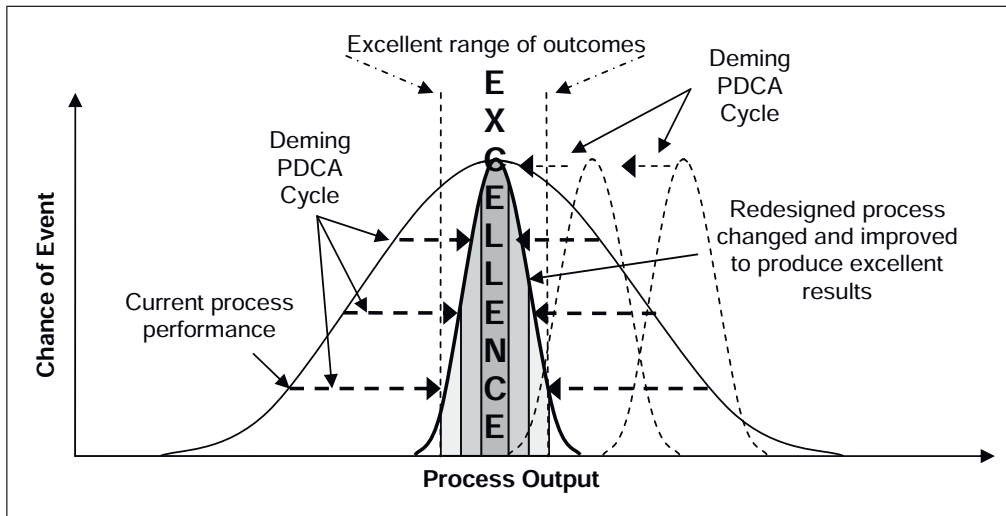


Figure 7.6 – Processes can be changed to Deliver Excellence.

If a business process produces excessive errors, for example there is too much rework from poor quality, it is vital to investigate if it failed to meet the standard because of a process problem or a special cause problem. In his book 'Out of the Crisis' Deming provided an example of analysing the error rate per 5000 welds from eleven welders<sup>43</sup>. Figure 7.7 shows his analysis on a Shewhart control chart. Deming calculated the process error limits and put the upper control limit at 19; implying the process error naturally lie between 0 and 19 errors per 5000 welds. Any results less than 19 errors per 5,000 welds were within the process variation and were normal results from the process. Nothing could be done about it because that was how the process was designed – it could make anything from 0 to 19 errors due to its natural volatility. Those results outside of the process limits were special-cause related and needed to be corrected.

Deming used the control chart to get the process to talk to us. He was showing us how to understand our businesses and its performance. Error in a process is a random event and the probability of errors forms a normal distribution. By showing error on a control chart and defining the 3-sigma limits of the normal distribution the data belongs to, you can immediately see if the error is likely caused by the system volatility or by something outside the system. If it was a system cause then the data falls within the natural normal distribution of errors produced by the system – it is within the number of errors you would expect from running the process normally. If it is a system error it is no one's fault – it is just how the system works due to its design. Only the performance of Welder 6 is unexplainable, all the other welders have made no more errors than the system was designed to make. Special causes are affecting the performance of Welder 6 that need correction.

<sup>43</sup> Deming, W Edwards., 'Out of the Crisis', MIT Press, 2000 edition, Pg 256.

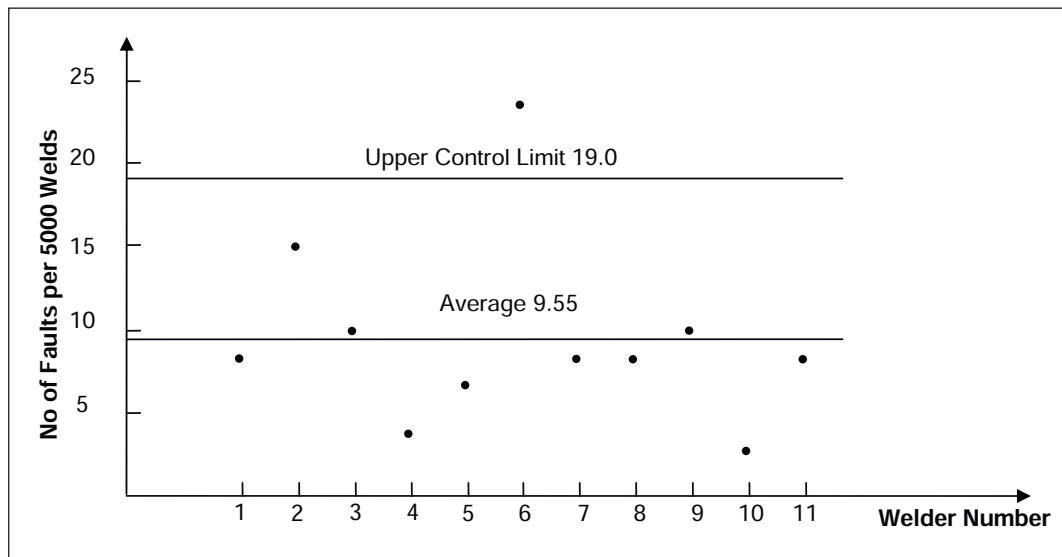


Figure 7.7 – Welding Process Control Chart.

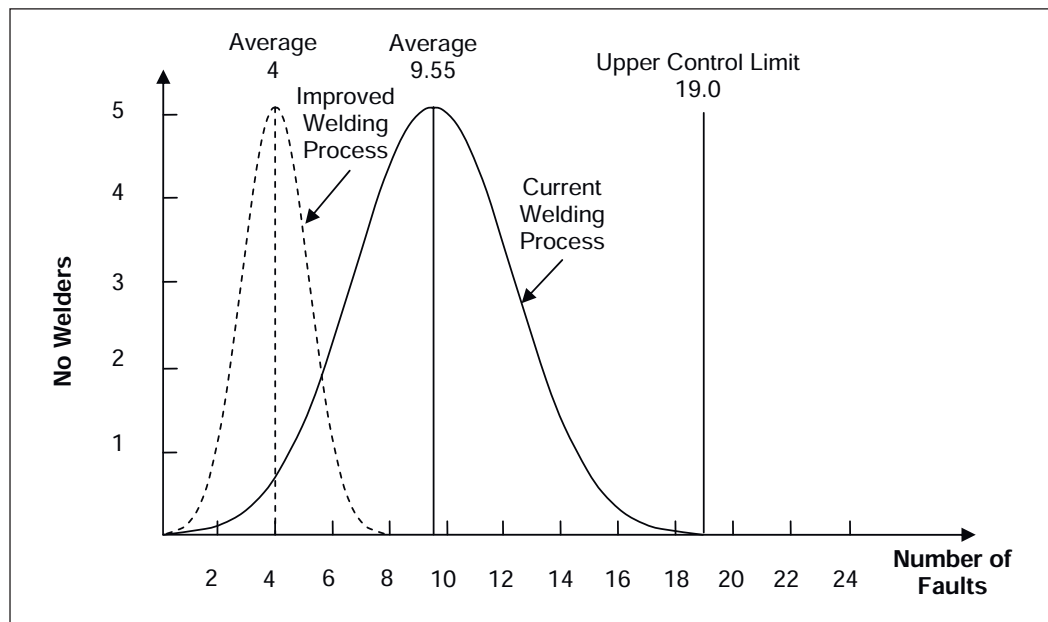


Figure 7.8 – Welding Fault Distribution.

Deming never blamed people for poor performance, he knew that the vast majority of faults lay with the system design in which they worked (by his estimate 94% of errors were system caused). Deming suggested the investigation consider two issues. The first was to look at the work stream to see if it was exceptionally difficult material to weld or the welds were in difficult locations. If the job difficulty was the problem then no more needed to be done because the problem was not with the person and as soon as the job returned to normal the welder's performance would too. The second factors to examine were such things as the condition of the equipment being used, the quality of his eyesight, and other handicaps, like problems at home or his health. To get fewer weld failures from the group of welders it would be necessary to change the design of the process to one with lower average number of faults.

Figure 7.8 shows the measured welding results assuming the frequency of failures matched a normal distribution. It also shows the new distribution if the process was redesigned to

produce an average of four faults per 5000 welds. To move from the current average of 9.55 faults per 5000 welds to an average of 4 would require an improved process with much less variation than the existing one. Deming said “overall improvement ... will depend entirely on changes in the system, such as equipment, materials, training.” He listed possible factors to consider, including getting the eyesight of all welders tested, reducing the variation in material quality, changing to material that was easier to weld, providing improved welding equipment, developing better welding techniques and retraining poor performers.

To have an operation where good results are natural and excellence abounds it is necessary to ensure variation in a process is controlled to within the limits that deliver excellence. It requires that a standardised system of producing excellence is developed and then followed. In a series process this means accuracy in every step, without which one cannot get excellent process outputs. World-class operations recognise the interconnectivity amongst processes and work hard to ensure everything is right at every stage in every process. This was Deming’s purpose – to help businesses learn to control variation so they always produced top quality products that customers love. This too is our job – to help our business learn to control variation and deliver the quality performance that our customers love.

### **Script and Write the Future You Want**

To attack unwanted variation specify exactly what is required and how to get it; script the desired performance. Variation starts to be controlled when management set clear and precise standards. The best practices to achieve the required outcomes are then developed by management and workers in collaboration and taught to people. Those best practices are the one agreed way to do a job so special cause variations are not introduced. The script is the start of delivering supreme performance. Achieving success is almost certain once you know what it looks like and how to get there.

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 better reliability performance of all equipment and processes. Anything that is not up to that standard is changed and improved to meet it.

### **Set the Risk Management and Quality Standards Required**

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 happens.

Table 7.1 – Sample List of Documented Standards in a World-Class Industrial Process Plant.

Technology and Facilities Safety System	Electrical	Fire and Explosion	Environmental	Product Stewardship	Distribution	Occupational Safety, Health and Industrial Hygiene	Asset Productivity Standards	Capital Effectiveness Standards
<ul style="list-style-type: none"> <li>Process Hazards Analysis</li> <li>Standards and Guidelines</li> <li>Process Safety Management Implementation</li> <li>Continuous Improvement Process</li> <li>Management Commitment and Responsibility</li> <li>Facility Positioning Studies</li> <li>Inherently Safer Processes</li> <li>Emergency response Planning</li> <li>Integrated SHE Organization</li> </ul>	<ul style="list-style-type: none"> <li>Electrical Safety Training and Consultation</li> <li>Incident Investigations</li> <li>Audits Using Best Practice Protocols</li> <li>Electrical Safety Standards/Guidelines</li> <li>Short Circuit Studies</li> <li>Time/Current Coordination</li> <li>Arc Flash Hazards</li> </ul>	<ul style="list-style-type: none"> <li>Fire and Explosion Incident Investigation</li> <li>Fire and Explosion Modeling, Detection, and Suppression</li> <li>Fire Safety Audits</li> <li>Fire Safety Training</li> <li>Life Safety</li> <li>Occupant Notification and Egress</li> <li>Emergency Preparedness and Response</li> <li>Fire Safety Management Systems</li> </ul>	<ul style="list-style-type: none"> <li>Environmental Permitting</li> <li>Environmental Solutions</li> <li>Environmental Management System Assessment</li> <li>Air Dispersion Modeling</li> <li>Exposure/Risk Assessments</li> <li>Water Quality Treatment</li> <li>Ground Contamination Remediation Planning</li> <li>Solid Waste Management</li> </ul>	<ul style="list-style-type: none"> <li>Senior Management Support</li> <li>Internal Communications</li> <li>Product Review Systems</li> <li>Risk Characterizations and Risk Management</li> <li>Systems for Training and Refreshing</li> <li>R &amp; D Systems</li> <li>Joint Ventures</li> <li>Sustainable Growth Initiatives</li> <li>Standards and Guidelines</li> </ul>	<ul style="list-style-type: none"> <li>Regulatory Training</li> <li>Standards and Guidelines</li> <li>Risk Assessments</li> <li>Transport Safety</li> <li>Emergency Preparedness</li> </ul>	<ul style="list-style-type: none"> <li>OSH Injury and Illness Reporting, Classification, Investigation, and Documentation</li> <li>OSH Roles, Responsibilities, and Accountabilities</li> <li>Metrics of OSH Management</li> <li>OSH Audit Protocols</li> <li>Medical Programs for Fitness Duty, Surveillance, and Emergency Care</li> <li>OSH Records and Communications</li> <li>Effective Wellness Programs</li> </ul>	<b>Maintenance and Reliability System</b> <ul style="list-style-type: none"> <li>Work Management Processes</li> <li>Managing Storeroom Supplies Effectively</li> <li>Reliability-Focused Maintenance</li> <li>Uptime Measurements</li> <li>Preventive/Predictive Maintenance Strategies</li> <li>Reliability Growth</li> </ul> <b>Manufacturing Capacity</b> <ul style="list-style-type: none"> <li>Material and Product Flow Analysis</li> <li>Continuous Flow</li> <li>Manufacturing and LEAN Manufacturing</li> <li>Industrial ergonomics</li> <li>Warehouse/Distribution Analysis</li> <li>Manufacturing Systems Simulation / Visualization</li> </ul> <b>Energy Optimization</b> <ul style="list-style-type: none"> <li>Steam Generation</li> <li>Electrical Power Distribution</li> <li>Refrigeration</li> <li>Cooling Towers</li> <li>Heating, Ventilating, &amp; Air Conditioning (HVAC)</li> </ul> <b>Facilities Infrastructure</b> <ul style="list-style-type: none"> <li>Groundwater Protection: trenches / sumps / dikes; tank foundations; sewers</li> <li>Structural Integrity and Architectural Components</li> <li>Transportation Systems: roads/pavements; railroads</li> <li>Power/General Services: PG&amp;S equipment &amp; systems; electrical power equip &amp; systems; HT/AC equipment &amp; systems;</li> </ul>	<b>Business Planning</b> <ul style="list-style-type: none"> <li>Business Objectives</li> </ul> <b>Facility Planning</b> <ul style="list-style-type: none"> <li>Project Objectives</li> <li>Project Capital Budget.</li> </ul> <b>Project Planning</b> <ul style="list-style-type: none"> <li>Production Design Basis</li> <li>Authorization Estimate</li> </ul> <b>Project Implementation</b> <ul style="list-style-type: none"> <li>Production Design</li> <li>Procurement</li> <li>Construction.</li> </ul> <b>Start-up and Initial Operations</b> <ul style="list-style-type: none"> <li>Plant Commissioning, Operations, and Maintenance</li> </ul> <b>Value Improving Guidelines</b> <ul style="list-style-type: none"> <li>Technology Selection</li> <li>Process Simplification</li> <li>Classes of Facility</li> <li>Quality</li> <li>Waste Minimization</li> <li>Constructability Reviews</li> <li>Process Reliability Modeling</li> <li>Minimum Standards &amp; Specifications</li> <li>Predictive Maintenance</li> <li>Design-to-capacity</li> <li>Energy Optimisation</li> <li>3D CAD Modeling</li> <li>Value Engineering</li> </ul> <b>Contractor Effectiveness Shutdown/Turnaround Practices</b>



You need to document and explain exactly how all your business processes will be run to get the required business outputs. They must be scripted precisely as things need 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 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.

Table 7.1 lists the types of procedures and documents to write for an industrial operation.<sup>44</sup> There are 105 document types listed. Without such documents, and the procedures that stem from them, there will be numerous interpretations of what is acceptable performance. Lack of clarity breeds wide variation and causes defects, problems and ‘fire-fighting’, as one thing goes wrong after another. With standardised, high quality procedures variation is controlled. Better methods can be developed to stop deviation and prevent failures. The lists in Table 7.1 represents a great deal of work. But such documents introduce and apply defect elimination and failure prevention throughout a business, and you cannot do without them. World-class operations will do the work, ‘also-rans’ won’t bother because they mistakenly think it is not a prerequisite to becoming world-class. They are wrong of course, and their thinking explains why they are where they are. They will remain ‘also-rans’ until their values and beliefs change and they do the work that is necessary.

Another mistaken belief is to see detailed documented procedures as the death of human creativity. Many people think they know all they need to know about their job and the best way to do it. They may be right. They do know a way to do their jobs. Whether it is the best way will depend if they have kept up with growing knowledge in the fields of research and technology that apply to the job, and then regularly introduced appropriate changes. A world-class company challenges its people to find even better ways to do their work. They know that the people doing a job are their resident experts and they want them to use their creativity to discover ever superior methods and procedures. Creativity does not die once procedures are introduced; rather it is funnelled into continually improving them toward yet better quality, for lower cost and at faster rates.

You now know what makes world-class businesses. They use sure methods and systems that deliver the performance standards their customers want. Then they keep lifting the standards and improving the systems. World-class operations use the scientific method, and not accidents of good fortune, to get lower-cost, on-time, quality production.

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<sup>44</sup> Maximising Operational Efficiency Presentation, E. I. Du Pont de Nemours and Co, 2004.



## The Enterprise Asset Management Toolkit

Managers use Plant Wellness, Asset Management and Quality Management methods and systems to get outstanding plant and equipment reliability. Figure 7.9 lists the main tools and when in the life cycle to use them. They let you set the standards that deliver world-class performance and build the business processes and skills to achieve it.

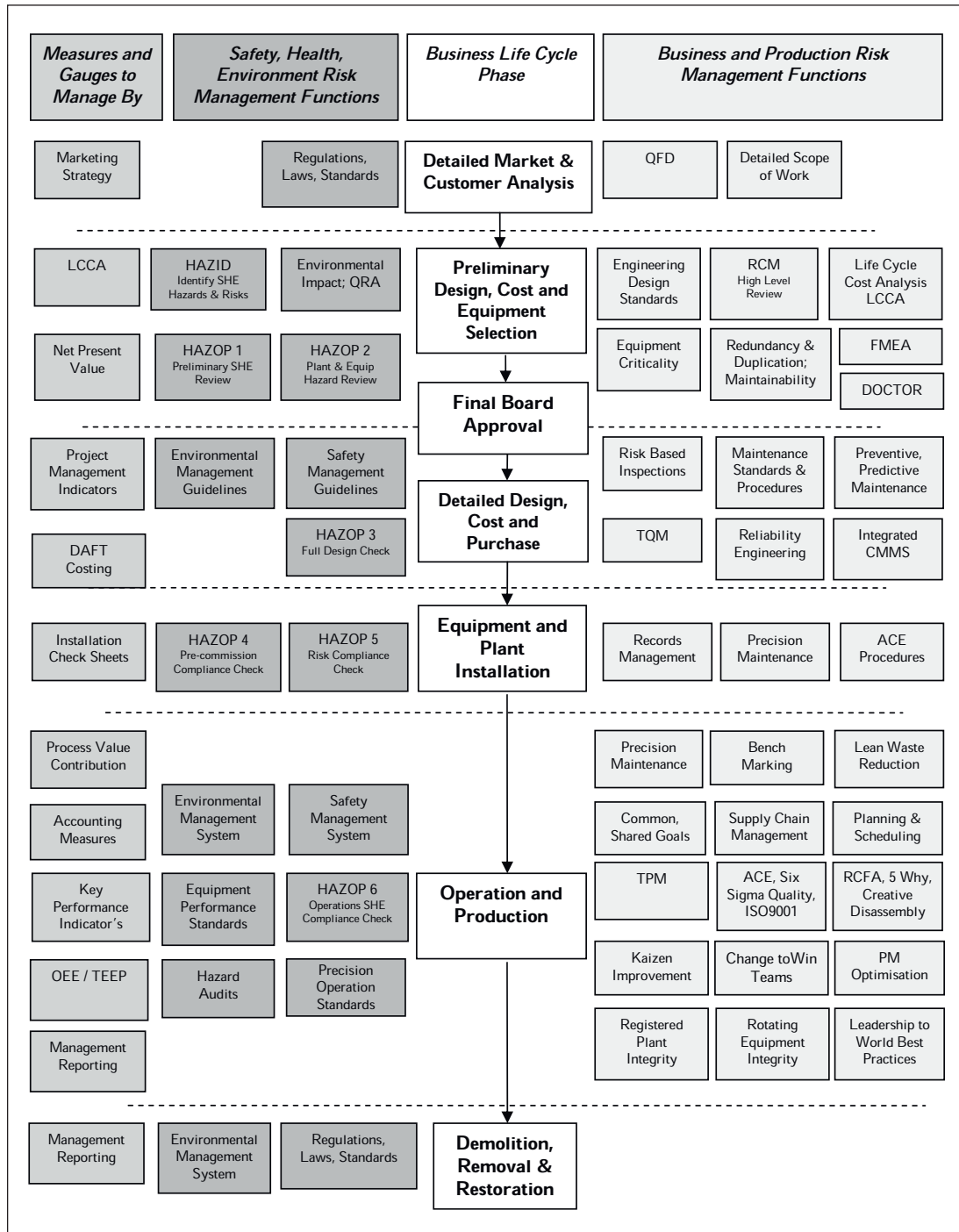


Figure 7.9 – Enterprise Asset Management Tool Kit.

On the left-hand side of Figure 7.9 are feedback and feedforward measures to gauge and manage a business. To the right are techniques and practices that produce compliance to the safety, health and environmental (SHE) requirements. Further to the right is a simplified life-cycle of an industrial business. It starts with the concept and financial justification for a project, through its design, commissioning, operation, and finally its de-commissioning. On the far right-hand are the methods, practices and systems that reduce business risks and deliver outstanding equipment reliability and plant performance. Short descriptions of ‘tool kit’ items not explained elsewhere in this book are in the Glossary.

### Detailed Market and Customer Requirements Analysis

Designers of products and designers of production plants need to be sure that what they build will meet customer and legal requirements. This is achieved by asking the customer what they want and documenting it. Once the requirements are specified in writing the designer has clear indication of the characteristics and attributes they must deliver in the product or the plant. The legal, safety and community issues are addressed in applicable legislation and international engineering standards.



Figure 7.10 – Know the Needs of Your Customer by Asking and Listening to Them.

### Quality Characteristics – The Determinants of Quality <sup>45</sup>

Customers decide if a product or service has quality. Table 7.2 lists some of the attributes they seek and use to confirm to themselves that it is a quality product or service. If the attributes are not there the product or service is poor.

Table 7.2 – Some Quality Attributes Customers Want from Designers.

Product Quality Characteristics			
Accessibility	Emittance	Producibility	Strength
Availability	Flexibility	Reliability	Taste
Appearance	Functionality	Reparability	Testability
Adaptability	Interchangeability	Safety	Traceability
Cleanliness	Maintainability	Security	Toxicity
Consumption	Odour	Size	Transportability
Durability	Operability	Susceptibility	Vulnerability
Disposability	Portability	Storability	Weight
Service Quality Characteristics			
Accessibility	Competence	Effectiveness	Responsiveness
Accuracy	Credibility	Flexibility	Reliability
Courtesy	Dependability	Honesty	Security
Comfort	Efficiency	Promptness	

<sup>45</sup> Hoyle, D., 'ISO Quality Systems Handbook', Butterworth-Heinemann, 5<sup>th</sup> Edition.

Available techniques that attempt to get the ‘voice of the customer’ echoed into the design and manufacture of the product include writing detailed scopes of work that specify required outcomes, and applying the structured method of Quality Function Deployment (QFD). It is critical that designers know what the customer wants and that sufficient effort is put into clarifying and recording their needs before time and effort is put into developing a solution. If the designer is not sure what a client wants they can waste a lot of time doing the wrong thing. Delivering the quality that a customer wants is a process. Specify the attributes needed of products and work. Define how to control, assure, improve, manage and demonstrate their achievement. Script what is required and how to deliver it and then do it. Figure 7.11 overviews the factors that need to be considered in designing a process to satisfy customers.

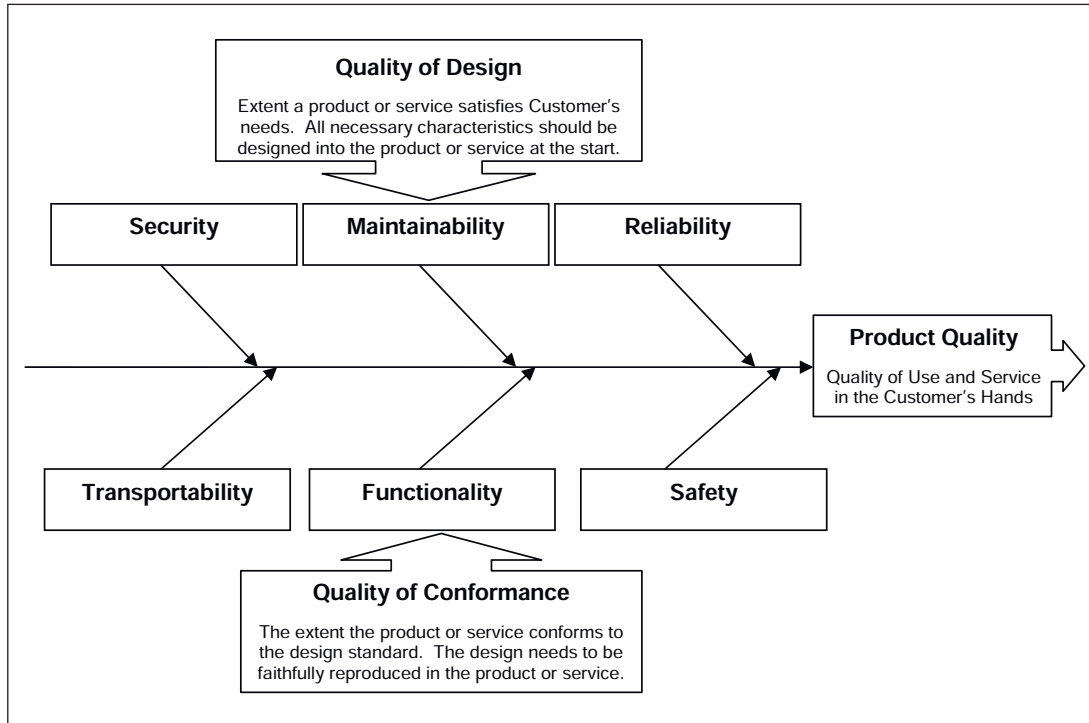
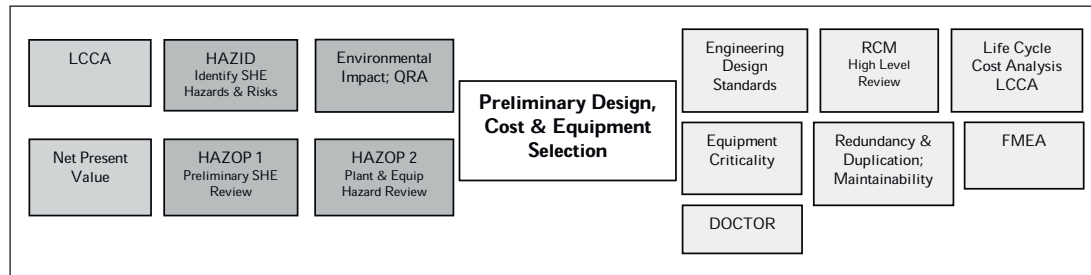


Figure 7.11 – Customers Determine Quality.

### Preliminary Design, Costing and Equipment Selection

The design and selection phase is a most critical period in the long-term success of a business. This is the stage that will determine its future operating costs and profitability. The choice of technologies, the choice of production processes, the choice of location, the choice of equipment to make the product mix will fix the facility's cost structure. It is at this point that the facility's future profits, and its future options to adapt in response to changing market forces, are set. If the equipment chosen for the facility requires major up-keep, or if the equipment cannot maintain quality production for great lengths of time, then the facility will produce high cost product and much waste. Production will produce less operating profit since part of their profit margin must pay for the up-keep of the facility and its equipment. There will be less cash available to make future business and plant improvements and so make products more competitively. In time, the products will disappear from the market because competitor items are cheaper and of better quality.



*Figure 7.12 – Preliminary Design, Costing and Equipment Selection.*

## Business Risk Reduction Strategies

The odds of making the right business choices at the Preliminary Design, Cost and Equipment Selection stage improve by using proven successful risk reduction strategies.

1. Apply Engineering Design Standards to permit standardisation throughout the facility,
2. Establish Equipment Criticality using DAFT Costing to highlight bottlenecks and equipment critical to success. Include the necessary production risk controls in the project justification.
3. Apply Failure Mode and Effects Criticality Analysis (FMECA) reviews on process and equipment and design-out problems or allow funds to maintain equipment at the level that will produce the production rates and quality required for project profitability.
4. Ensure the original equipment manufacturer (OEM) uses Failure Mode and Effects Analysis (FMEA) right down to the individual equipment component level to remove all foreseeable modes of equipment failure and their associated cost. By having the OEM perform the FMEA and getting their designs right, you will know that you are buying highly reliable equipment that will have low operating costs.
5. Model Life Cycle Cost Analysis (LCCA) by people experienced in using and maintaining the equipment to make the best life-long profitable equipment choices for the business.
6. Use Duplication and Redundancy wisely where functional failure is unacceptable to the financial return for the project. Use the process maps to find opportunity to apply parallel reliability strategies. For example, include tie-in points to use mobile equipment during breakdowns and preventive maintenance servicing. Design the plant and process so there are duplicated systems and circuits that keep production going even if one circuit is lost.
7. Optimise operating costs with the DOCTOR. Maximise maintainability of plant and equipment to speed-up maintenance actions and reduce outage times. Simplify repairs so that operators can do them. Remove costly special access requirements. Ensure the plant is maintainable without shutting down large portions of it.

## Controlling Safety, Health and Environment Risk

The likelihood of future Safety, Health and Environment (SHE) problems are controlled and mitigated by:

1. Performing Environmental Impact Studies and Qualitative Risk Assessments (QRA) to highlight potential risk to the community and environment.

2. Conducting Hazard Investigation (HAZID) risk management analysis of potential dangers with the proposed design.
3. Applying Hazard and Operability (HAZOP) reviews of proposed plant and operating practices to insure safe outcomes in event of upset situations occurring during operation.

## Measures and Gauges

Selecting good long-term production, process and equipment decisions depends on finding the least expensive life cycle cost that meets product quality and throughput requirements. The financial benefits and effects on the viability of a project from addressing SHE and business risks can be estimated and optimised by using the DOCTOR and modelling the Net Present Value of future profits from each option.

## Detailed Design, Costing and Purchasing

Once the Board accepts the marketing analysis and cost justification of the preliminary engineering design, the project goes into the detailed design and procurement phase. The complete engineering is finalised so materials and equipment can be purchased and sent to site for construction and installation. The detailed design, costing and purchasing phase produces all the final drawings, construction specifications, equipment specifications, purchasing and supply contracts, operating standards and procedures, maintenance standards and procedures. This ensures that from the first day the operation reliably produces quality product to meet the cash flow expectations of the business.

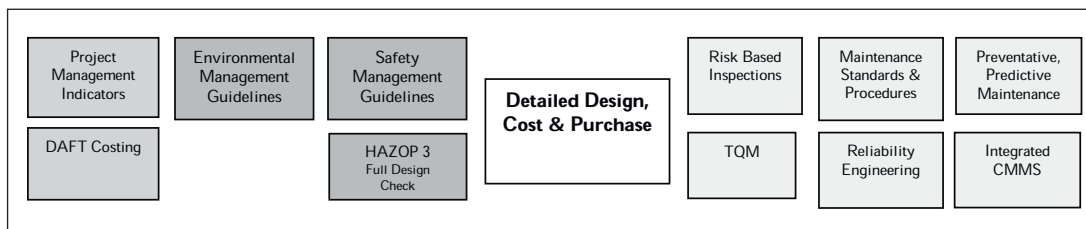


Figure 7.13 – Detailed Design, Costing and Purchase.

## Business Risk Reduction Strategies

At this point in the project it is necessary to go into detail and specifics with care, and a desire to build a world best operation and facility. The tools available to manage business risk include:

1. Maintenance Standards and Procedures defining and specifying the operating tolerance of plant and equipment. They establish the benchmark requirements to keep the facility in a condition to meet its community, safety, environmental and business obligations.
2. Risk Based Inspections (RBI) that quantifies the likelihood of catastrophic plant and equipment failure so you can set into place suitable inspection periods and procedures.
3. Using Total Quality Management (TQM) to set and control quality requirements for the equipment, processes and systems in the facility.
4. Developing Preventative Maintenance (PM) routines to prevent ageing and usage failure through vigilant equipment care and observation.

5. Instigating proactive Predictive Maintenance (PdM) inspections to forewarn of future process, plant and equipment problems.
6. Installing an integrated Computerised Maintenance Management System (CMMS), as part of an Enterprise Asset Management (EAM) System, to manage and track the facility's production and maintenance requirements and associated costs.

### **Controlling Safety, Health and Environment Risk**

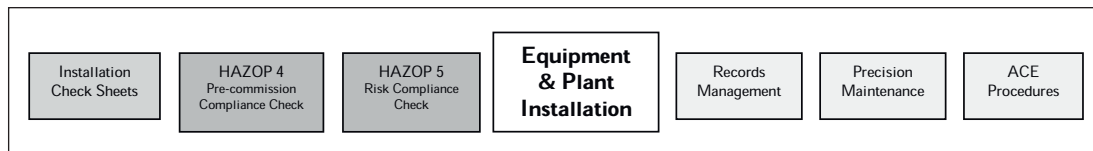
To manage SHE risk it is necessary to have both safety and environmental guidelines to meet during detailed design. Once a process design is firm it is time to conduct an in-depth and detailed Hazard And Operability Study (HAZOP) of each process item to check it will perform to its design requirements during operation, and insure the protection of people and environment if it does not. The HAZOP risk review methodology is a well-used and successful risk identification and management tool applied at the drawing board level of a facility's design.

### **Measures and Gauges**

The whole process of designing, specifying and purchasing project infrastructure, goods and services is project managed.

### **Plant and Equipment Installation**

The project has now progressed to the field work stage. The site is prepared, buildings constructed and plant and equipment installed in place. Poor workmanship and quality control during construction and installation will produce excessive maintenance and production downtime in future.



*Figure 7.14 – Plant and Equipment Installation.*

### **Business Risk Reduction Strategies**

At this point, it is critical to ensure the equipment goes into place to world class installation and maintenance practices and standards. This level of professionalism will guarantee that the equipment operates within its design requirements all its working life.

### **Accuracy Controlled Enterprise**

Document the procedures that, if followed, will deliver highly reliable equipment operation. From commissioning ACE quality practices must be in use. Train people to the 3T – Target, Tolerance Test – procedures so they always deliver the required quality performance.

## **Precision Maintenance**

The installation standards needed are those of Precision Maintenance. They cover the requirements for fastener tension, shaft alignment, rotating equipment balancing, equipment operating vibration limits, lubrication and equipment frame stresses and distortion. It is necessary to specify these requirements to both the original equipment manufacturer and the equipment installation contractor. Internationally recognised standards are available.

## **Records Management**

Protect the engineering, operating and maintenance knowledge base developed during the design process by the use of sound records management practices. Correct information will be the lifeblood of the facility management's future ability to make good, timely decisions. It is terribly important to preserve all the facility's design and equipment selection information for the facility's entire existence. Similarly, all the operating and maintenance standards and procedures established during the design phase must be readily available during commissioning and in later operation.

The best record management practice is to centralise the storage and care of the master documents but make all necessary information (project, engineering, operating, process and maintenance) easily available and widely distributed electronically. When questions arise and decisions are to be made in future, complete and accurate information must be quickly on-hand.

## **Controlling Safety, Health and Environment Risk**

At the end of construction and installation, it is necessary to confirm and prove that hazards identified previously are under control. Further HAZOP studies and check tests conducted during commissioning to prove compliance.

## **Measures and Gauges**

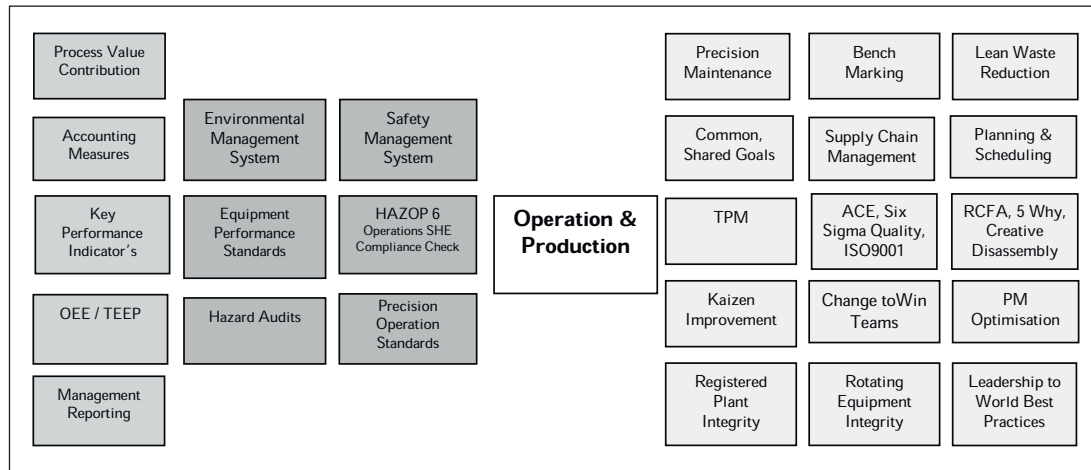
Because this is part of the project construction phase, the existing project management measures and controls monitor compliance to the project plan.

Maintain control of the precision and quality of installation with check sheets. On the check sheets, record the previously set standards and equipment design requirements. Take site measurements and compare them to the standard to ensure the work meets precision maintenance and engineering standards. If site results do not meet the standard, correct the problem until compliance.

## **In Operation and Production**

At this point, the plant is fully operational and making product. This is when profits are generated to payback the capital used to create the business and make a return on the investment. Typically, a manufacturing or processing plant operates for several decades. The equipment always needs to be in suitable operating condition when it has to perform its function. To prevent equipment failures, production outages and product quality problems the business processes in use must control variation to within specification. If that is not possible then the business processes must be redesigned until the outputs comply with requirements.





*Figure 7.15 – During Operation and Production.*

### Business Risk Reduction Strategies

A large range of methodologies and practices are available to Operations and Maintenance to manage, control and adjust processes and equipment to produce product within specification <sup>46</sup>.

#### The business risk controls available include:

1. Leadership and guidance to maintain a world class effort;
2. Common, shared goals across all departments so all strive for the same result;
3. Lean Manufacturing practices and methods to reduce waste in all its forms;
4. Total Productive Manufacturing (TPM) loss minimisation through worker empowerment;
5. Six Sigma Quality control that targets well above average compliance to specification;
6. Kaizen continuous improvement projects in the workplace. The workplace is where the problems exist, where they can be seen, and where the people are most likely to come up with workable answers;
7. Root Cause Analysis (RCA) fault removal to find and break the causal trails that occur in all failures and faults;
8. Preventative Maintenance Optimisation to focus on preserving the key functions of the equipment;
9. Benchmarking against others in the industry to check the right things are being done and that performance is at a high standard;
10. Supply Chain Management of raw materials and processes to deliver the best finish product to the client;
11. Planning and scheduling to ensure up-keep of plant and equipment.
12. Challenge paradigms and create a learning organisation with the 'Change To Win' process explained in the workbook on the CD accompanying this book.

<sup>46</sup> Moore, Ron., 'Making Common Sense Common Practice', Butterworth-Heinemann, 2002.

## **Controlling Safety, Health and Environment Risk**

SHE risk management requires religiously following the specified operating procedures, and by measuring and auditing the process, plant and equipment performance to prove they meet the set safe operating specifications and corporate standards.

## **Precision Operation Standards for Degradation Management**

Establishing Precision Operating Standards and Procedures to run the facility, plant and equipment in ways to meet its legal, community, environmental and business obligations is critical. Precision operation involves specifying and setting limits within which the process, plant and equipment is operated. This protects the assets from abuse and misuse and insures the viability of the operation for its lifetime. With the use of precision operation standards, the equipment runs in a condition that keeps it within the design envelope it was constructed and built to perform reliably.

## **Equipment Performance**

This includes making information on the equipment and process available in a visual form such as graphs and Pareto Charts (bar charts). An even more useful form of presenting important information is to trend a process variable against another affected by it. For example trending pump power usage against pump flow to indicate loss in performance as the internals of the pump wear. When the loss in performance is unacceptably far from the standard precision operating specification the equipment is rebuilt and brought back to as new again, or replaced.

## **Hazard Audits**

Systems degrade over time. New people come in and new ideas and methods develop. The importance of past decisions becomes less relevant as time passes. This is a natural process of evolution and learning. The danger is that the original requirements designed into the plant and its production systems, which were meant to manage business risk and control hazards to protect the business, its people and its assets, are lost. Businesses have lost entire production facilities and people have died because the organisation did not do key hazard control requirements<sup>47</sup>. It is critical that management knows the status of the risk management practices and the risk control methods used by its employees.

Regular auditing is the only way to prove that the important aspects of business and safety risk management requirements are in common use in your operation. When auditing look for proof of non-compliance, not proof of compliance! It is easy to show a record of a system working as designed. But it's more important to look for evidence that it is not working to specification and correct the problems causing it.

## **Measures and Gauges**

The importance of maintaining continual vigilant control over the operation reflects in the range of measures used to monitor and address variability of the operation. The measures to use include:

1. Key Performance Indicator (KPI) trends showing whether processes and systems are in or out of control,

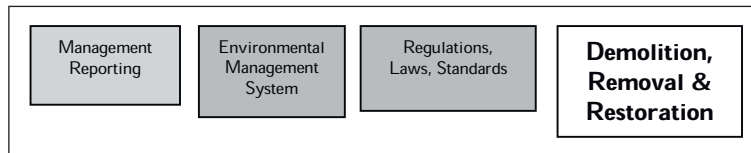
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<sup>47</sup> Hopkins, Andrew, 'Safety, Culture and Risk – The Organisational Causes of Disasters', CCH Australia, 2005.

2. Overall Equipment Effectiveness (OEE) measure to quantify the whole operation's ability to have the plant availability, product quality and production performance necessary to make what the customer wants.
3. Accounting measures such as profit, cash flow, return on assets, cost control, inventory control and many more.
4. Management reporting, which becomes a critical factor in monitoring and maintaining compliance to set and agreed procedures and policies.

### **Demolition, Removal and Restoration**

At this stage in the life of a facility the equipment is old, but if properly maintained and used during its service life it is still in good condition and able to deliver production at the same throughput, quality and specification as if new. There is no reason that old equipment properly maintained, replaced when fatigued, and run as designed without overdue stress to its materials of construction, should not retain the same capacity and abilities as it had at the start of its life.



*Figure 7.16 – Demolition and Rehabilitation.*

## 8. Operating Equipment Risk Assessment

Risk is an amount of loss or gain. The presence of risk does not imply certain loss. The risk of having money invested in the stock market brings with it the possibility of great reward as well as the possibility of serious loss. The challenge is to develop methods to increase the likelihood of good outcomes while controlling and removing the bad. Because risk has such profound impact in everything to do with business and commerce it is critical to understand it. Once you have a good perspective on risk you are better able to identify the risk management strategies that provide the greatest financial, production and safety benefits to your organisation.

Risk is virtually impossible to reckon exactly because it is probabilistic – a situation might happen, or it might not. 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.

### The Risk Equation

The most commonly used form of the risk equation is:

$$\text{Risk} = \text{Frequency of Occurrence (/yr)} \times \text{Consequence of Occurrence (\$)} \quad \text{Eq. 8.1}$$

Risk is equal to the frequency of an event occurring multiplied by its cost, should it occur. Frequency is the number of times an event actually happens during a period. Usually a year is used. An event that happens every five years has a frequency of 0.2 times a year. The consequence of an occurrence is the total financial impact of the event – its DAFT Costs. By calculating the frequency of an event per year, and counting consequence of the occurrence in monetary value, the equation measures the annual cost of risk. It is a means to quantify the yearly cost to the organisation of every event it suffers, good or bad. It provides a figure to gauge one risk against another and so allows the setting of priorities for addressing risk.

The ‘Frequency of Occurrence’ divides further so the risk equation becomes:

$$\text{Risk} = [\text{No. of Opportunities (/yr)} \times \text{Chance of Occurrence}] \times \text{Consequence (\$)} \quad \text{Eq. 8.2}$$

The ‘Number of Opportunities’ is how many times a year the situation arises that could lead to a failure. The ‘Chance of Occurrence’ (or Probability) is the odds that a situation will go through to failure. It is one (1) if it will definitely fail every time the situation arises, and zero (0) if there will never be a failure when the situation arises. It normally takes values between 1 and 0 because the chance of a thing happening is usually possible to some degree.

There are great benefits available to businesses that reduce their risk of failure. If the chance of a failure is reduced so it happens less often it saves money because there are fewer events to spend it on. Using a simple example of a failure event that happens twice a year and costs \$10,000 each time it occurs, the standard risk equation gives:

$$\text{Cost of Risk} = 2 \text{ events per year} \times \$10,000 \text{ per event} = \$20,000 \text{ per year}$$

By introducing risk reduction strategies that reduce the chance of the event to every two years, the risk becomes:

$$\text{Cost of Risk} = 0.5 \text{ events per year} \times \$10,000 \text{ per event} = \$5,000 \text{ per year}$$

The mitigation has delivered a saving of \$15,000 per year, year after year. This is how businesses can minimise their cost of operation and make a lot of money. If they can reduce the numbers of failure events, or lower the cost of those events, then the risk to the operation reduces. If in the example the cost of reducing the risk to once every two years is less than \$15,000 a year, then the company has made money by saving it. Controlling failure and controlling risk have identical implications to a business – reduce the numbers of failures and cost falls; reduce the amount of risk and cost falls. The challenge is to select those strategies that cost the least but realise the greatest risk reduction.

When a normal risk analysis is conducted the values for each part of the risk equation are developed using information available about the situation under review. Table 8.1 shows the typical column headings of a risk assessment spreadsheet used to gauge risk for operating equipment.

*Table 8.1 – Risk Calculation Spreadsheet Layout.*

Ref No	Equip Tag No	Equip Desc	Failure Event or Causes	Cost Consequence of Failure (\$)	Years Equip in Service or Expected	No of Historic Failure Events at this Site or Expected	No of Annualised Failure Events due to Cause (/ Yr)	Likelihood of Failure Event (Between 1 – 0)	Estimated Inherent Risk (\$/Yr)
1	2	3	4	5	6	7	8	9	10

The ‘Equipment Tag Number’ (Column 2) is the equipment number given to each item of equipment at that site. Every Tag No. is included – machinery, electrical equipment, instrumentation, piping, even the buildings and each functional area in a building.

The ‘Equipment Description’ is the official descriptive name used to identify the equipment.

The ‘Failure Event or Causes’ is the separate ways in which an item of equipment has failed, or could fail, in the situation it is in. For example, a two-wheel bicycle can fail due to a tyre puncture, a road accident, a chain drive failure, and so on.

The ‘Consequence of Failure’ is the cost impact when the equipment fails due to the cause.

The ‘Years Equipment in Service or Expected’ is the count of years the equipment has been in use. For new equipment items the expected years in service is used. Work in whole numbers and round any part-year to the nearest full year.

The ‘Number of Historic Failure Events at the Site or Expected Due to Cause’ is determined for each failure event cause by interrogating the equipment history (e.g. from a Computerised Maintenance Management System – CMMS) or from industry failure databases adjusted for the quality culture prevalent in the operation.

The ‘Number of Failure Events per Year’ is from dividing the ‘Number of Historic Failure Events at the Site’ by ‘Years Equipment in Service’ values.

The ‘Likelihood of Failure’ is a determination from tables such as Table 8.2, developed using risk analysis methodology from international risk management standards and industry guides<sup>48, 49</sup>.

<sup>48</sup> Australian Risk Management Standard AS4360:2004.

<sup>49</sup> Robinson, Richard M., et al, ‘Risk and Reliability: An Introductory Text’, R2A Pty Ltd, 7<sup>th</sup> Edition.

Table 8.2 – Determining the Likelihood of Equipment Failure on a Site.

Risk Level	Descriptor	Description	Indicative Frequency (expected to occur)	Actual Failures per Year (historic evidence basis)	Likelihood of Failure per Year (opportunity for failure basis)	
					Opportunities (No. of Times a Situation Arises)	Probability of Failure
6	Certain	Failure event will occur at this site annually or more often	Once a year or more often	1 or more	Count every time the situation for an event occurs	1 if failure results every time the situation arises
5	Likely	Failure event regularly occurs at this site	Once every 2 to 3 years	1 in 2 = 0.5 1 in 3 = 0.33	Count every time the situation for an event occurs	0.1 if failure results 1 in 10 times the situation arises
4	Possible	Failure event is expected to occur on this site	Once every 4 to 6 years	1 in 4 = 0.25 1 in 6 = 0.17	Count every time the situation for an event occurs	0.01 if failure results 1 in 100 times the situation arises
3	Unlikely	Failure event occurs from time to time on this site or in the industry	Once every 7 to 10 years	1 in 7 = 0.14 1 in 10 = 0.1	Count every time the situation for an event occurs	0.001 if failure results 1 in 1,000 times the situation arises
2	Rare	Failure event could occur on this site or in the industry but doubtful	Once every 11 to 15 years	1 in 11 = 0.09 1 in 15 = 0.07	Count every time the situation for an event occurs	0.0001 if failure results 1 in 10,000 times the situation arises
1	Very Rare	Failure event hardly heard of in the industry. May occur but in exceptional circumstances	Once every 16 to 20 years	1 in 16 = 0.06 1 in 20 = 0.05	Count every time the situation for an event occurs	0.00001 if failure results 1 in 100,000 times the situation arises

Determining the likelihood of failure is fraught with uncertainty. The opportunity for failure may rise often but never go to conclusion. Counting historic failure is easy because there are records. But counting an opportunity for failure that does not progress to a failure is open to speculation. An example of counting opportunities for failure is those known to be due to overload on equipment start-up. The likelihood of failure of a part known to fail from a high-stress overload during start-up can be calculated with Eq. 8.3. The opportunity for failure is the count of the average numbers of starts between failures. The likelihood of failure is:

$$\text{Likelihood of failure} = \frac{\text{No of failures}}{\text{Average number of starts between failures}} \quad \text{Eq. 8.3}$$

For an operation running continuously with 10 starts a day and failures averaging every 6 months, or twice a year, the likelihood of failure is:

$$= \frac{1 \text{ failure}}{1800 \text{ starts}} = 0.00056$$

With DAFT Cost of failure at \$25,000, the risk calculated by using Eq. 8.2 is:

$$\begin{aligned} \text{Risk} &= [\text{No. of Opportunities (/yr)} \times \text{Probability of Failure}] \times \text{Consequence (\$)} \\ &= 3600 \times 0.00056 \times \$25,000 = \$50,000/\text{yr} \end{aligned}$$

The \$50,000 annual risk estimated by first finding the probability is the same as that estimated by using the number of failures a year of Eq. 8.1 (i.e. 2/yr x \$25,000). Where failures have happened, it is easier to count the average 'Failures per Year' from historic evidence and use the number in the risk equation. Historic failures are used because they already reflect the risk present. Future failure rates will remain the same as in the past until better risk management strategies are put into use. Use the opportunity for failure approach of Eq. 8.2 if it is known how often a failure situation truly arises. But if the count of opportunities is uncertain then use the historic average failures per year for the site in Eq.8.1. If actual site failures are not

available, the industry average adjusted for the on-site culture can be used. If there is a good reliability culture and industry best practices are applied well, use the industry average; in a poor reliability culture assume a substantially worse outcome.

The ‘Estimated Inherent Risk’ is the annualised cost to the business of carrying the risk calculated by multiplying the values: ‘Number of Annualised Failure Events due to Cause’ x ‘Likelihood of Failure’. It is the yearly cost for the risk carried by the business, and is used for gauging the size of a risk and comparing it with others. Those risks that a business does not want to carry can now be identified and mitigation plans put into place to reduce them.

## The Risk Matrix

Knowing the ‘consequence’ and ‘frequency’ allows development of a risk ranking table for an operation. Table 8.3 is a risk matrix used to gauge the level of risk in a business. It is developed using the recommendations of international risk management standards. The business-wide consequences for people, reputation, business processes and systems, and financially are explained and scaled to reflect the organisation under review.

*Table 8.3 – Risk Identification and Assessment.*

<b>RISK MANAGEMENT PHILOSOPHY</b>  <b>E – Extreme risk – detailed action plan approved by CEO</b>  <b>H – High risk – specify responsibility to senior manager</b>  <b>M – Medium risk – specify responsibility to department manager</b>  <b>L – Low risk – manage by routine procedures</b>  <b>Extreme or High risk must be reported to Senior Management and require detailed treatment plans to reduce the risk to Low or Medium</b>		<b>Business-Wide Consequence</b>					
		<b>People</b>	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.
		<b>Reputation</b>	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.
		<b>Business Process &amp; Systems</b>	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.
		<b>Financial</b>	<b>\$5K</b>	<b>\$50K</b>	<b>\$100K</b>	<b>\$250K</b>	<b>\$500K</b>
			<b>Insignificant</b>	<b>Minor</b>	<b>Moderate</b>	<b>Major</b>	<b>Catastrophic</b>
		<b>Historical Frequency:</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>
Event will occur at this site annually or more often	<b>6</b>	<b>Certain</b>	<b>M</b>	<b>H</b>	<b>H</b>	<b>E</b>	<b>E</b>
Event regularly occurs at this site	<b>5</b>	<b>Likely</b>	<b>M</b>	<b>M</b>	<b>H</b>	<b>H</b>	<b>E</b>
Event is expected to occur on this site	<b>4</b>	<b>Possible</b>	<b>L</b>	<b>M</b>	<b>M</b>	<b>H</b>	<b>E</b>
Event occurs from time to time on this site	<b>3</b>	<b>Unlikely</b>	<b>L</b>	<b>M</b>	<b>M</b>	<b>H</b>	<b>H</b>
Event occurs in the industry, and could on this site, but doubtful	<b>2</b>	<b>Rare</b>	<b>L</b>	<b>L</b>	<b>M</b>	<b>M</b>	<b>H</b>
Event hardly heard of in the industry. May occur but in exceptional circumstances	<b>1</b>	<b>Very Rare</b>	<b>L</b>	<b>L</b>	<b>L</b>	<b>M</b>	<b>H</b>



The methods and principles to apply in addressing risk can be advised in the Risk Management Philosophy box to the left of the matrix. The risk matrix is used to gauge whether an item or situation is at low, medium, high or extreme risk. Extreme and high risk are reduced to medium and low respectively, and medium level risk is reduced to low. The numbers corresponding to each level of likelihood and consequence can be added together to provide a numerical indicator of risk. This is often useful for comparing dissimilar risks to set priorities. It is a simple means not involving mathematical calculation to give each risk a representative value.

Identifying events and grading their risks is done using Table 8.4.

*Table 8.4 – Risk Identification and Assessment.*

EQUIPMENT OR ASSEMBLY	THE EVENT OR FAILURE <i>What can happen?</i>	SOURCE <i>How can this happen?</i>	IMPACT <i>from event happening</i>	CURRENT CONTROL STRATEGIES <i>and their effectiveness</i> (A) – Adequate (M) – Moderate (I) – Inadequate	CURRENT RISK LEVEL			ACCEPTABILITY (A/U)
					LIKELIHOOD	CONSEQUENCE	CURRENT RISK LEVEL	
1	2	3	4	5	6	7	8	9

Table 8.5 is used to find strategies and actions to mitigate the risk and to judge their effectiveness. At the end of the review the risks and the mitigation actions are transferred into a Risk Management Plan spreadsheet, such as that for plant and equipment on the CD accompanying this book.

*Table 8.5 – Risk Treatment Schedule and Action Plan.*

EQUIPMENT OR ASSEMBLY RISK	POTENTIAL TREATMENT OPTIONS	COSTS & BENEFITS	TREATMENT TO BE IMPLEMENTED (Y/N) <i>and their effectiveness</i> (A) – Adequate (M) – Moderate (I) – Inadequate	RISK LEVEL AFTER IMPLEMENTED			RESPONSIBLE PERSON	TIMETABLE <i>to implement</i>	MONITORING <i>strategies to measure effectiveness of risk treatments</i>
				LIKELIHOOD	CONSEQUENCE	TARGET LEVEL			
1	2	3	4	5	6	7	8	9	10
FINAL Cumulative Risk Level after Treatment									

### A Practical Way to Use the Risk Equation

When risk is under-priced wrong decisions can result and insufficient protective measures are taken against the real likelihood of failure. Making decisions involving risk without understanding both the likelihood of an incident occurring and the full cost of its consequences have ominous implications to a business. In situations involving risk it becomes necessary to identify the various scenarios that may happen and estimate their individual cost and probability of occurring.

The risk equation requires its users to know the chance and the consequence before a risk can be determined. The cost consequence is the worst financial impact of the incident and found by assuming worst case scenarios and tallying costs using DAFT Costing. What is not easy to determine is the 'chance' factor for an incident. Because an incident requires several permitting causes to occur in sequence or together, and each has its own degree of chance, then the probability of all factors coming together is never more than a hopeful estimate, a guess. Few businesses want to operate on guess-work as their strategy for being profitable.

Typically, you look at the history of an incident and use recorded evidence to determine a frequency. Alternately, you can use industry databases if available and they are reflective of the situation under consideration. Where there is insufficient or no historic data for an incident, then laboratory and controlled trails and tests can estimate the conditions for a failure incident to occur. From the test you conduct a scientific analysis and engineering review to estimate a probabilistic frequency of the event. This is better than guess work, but no-one knows how much better because of the many assumptions needed to arrive at the estimated frequency figure.

We can be sure the consequence value is reasonably accurate if DAFT Costing is used to calculate the total cost. But we can never be certain that the frequency figure is correct, or even close to correct, unless there is a long, unchanged history of the incident occurring. If historic records are complete and accurate, you can use them as evidence of event frequency. For those loss incidents that hardly-ever happen, or happen infrequently, the estimated risk could be very wrong. The situation is further complicated by the fact that when the chance of the incident happening is altered by improvement projects, or by totally unknown events stemming from unrecognised causes, then the frequency figure changes too. It requires but one change to the factors influencing an incident and the event frequency can alter completely. This uncertainty raises the questions, "If the frequency figure in a risk equation is so uncertain why try and estimate it? Why base your decisions on something so unpredictable?" When the frequency is chancy then there is another way to use the risk equation to get value from it.

By simple mathematical manipulation of the risk equation:

$$\text{Chance} = \text{Risk} \div \text{Consequence}$$

With the equation written in this form we are in better command of risk. No longer do we need to wait in stressful expectation of a failure, wondering when it will happen. Instead, we decide the risk to carry in our business and then act to implement the risk control methods needed to produce that outcome. With the equation in the form above, we can decide what we want to pay for risk. We can set a risk boundary beyond which we will not tolerate. We become proactive against failure.

If we have a risk where the DAFT Cost consequence is \$100,000 but the frequency is uncertain, we can accept a guess for the frequency and hope it is right. Or we can decide that we do not want to carry a risk greater than \$10,000 per year and use the re-formatted the risk equation to identify the frequency we are prepared to accept.

$$\begin{aligned} \text{Chance} &= \text{Risk} \div \text{Consequence} \\ &= \$10,000 \text{ per year} \div \$100,000 \text{ per event} \\ &= 0.1 \text{ events per year (i.e. Once in ten years)} \end{aligned}$$

The frequency is no longer guesswork. Knowing we need ten years between events lets us develop and action risk mitigations that reduce the change of the event to the required

period. Resources and money can be devoted to accomplishing it with greater certainty of achievement. It is a more useful way to use the risk equation than hoping an estimate for frequency is close to being right, and wondering if the current business systems and practices will provide that level of protection. A second benefit of using the risk equation in this way is knowing how much to pay for risk control. For an event that costs \$100,000 to happen no more than once in ten years, you can afford to pay up to an equivalent \$10,000 a year, or \$20,000 every two years, or \$50,000 every five years to prevent it. If it costs more than \$10,000 annually to prevent the once-in-a-decade \$100,000 risk, it is necessary to identify and address the causes of the higher cost. If reducing the annual cost to mitigate the risk is not possible, then the risk is greater than was envisioned. As a risk rises, more money can be justified to reduce the likelihood of its occurrence.

### Risk Boundary

A DAFT Costs based risk analysis establishes the risk boundary that an organisation is willing to carry. If the risk is acceptable nothing is done to stop it and, should it happen, the business then knowingly pays for the rectification. But if the cost of failure is unacceptable, then mitigation is put into place to reduce it sufficiently, since mitigation to prevent the problem is seen as a better investment than paying to fix its consequences later. Figure 8.1 shows the risk boundary concept of investment to prevent failures. This company will not accept annual DAFT Costs on an item of equipment of more than \$20,000, and is willing to invest to reduce greater risks.

A business makes money if a risk can be prevented for less than the risk's equivalent annualised cost. The greatest opportunity for business to manage risk for much less cost is by identify those methods, systems and practices that reduce the chance of a risk arising, and then implement them with great energy and vigour across the organisation. Maintenance is only one of the methodologies available to reduce the risk of equipment failure. But it is a consequence reduction strategy and comes after failure has started. Also available are numerous engineering and operational choices that are more cost effective over the equipment life-cycle than maintenance because they use chance reduction strategies that stop failure from starting. (Chance Reduction Risk Management is explained in Chapter 11.)

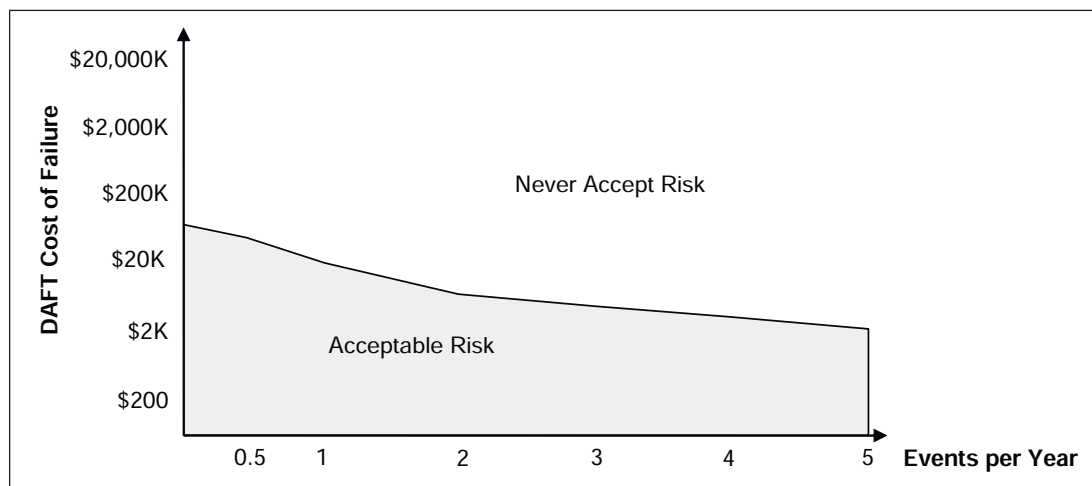


Figure 8.1 – The Risk Boundary Concept.

## Equipment Criticality

Developing an equipment risk profile is known as Equipment Criticality. It uses the risk formula to identify the financial impact if an equipment failure was to happen – it is a risk rating indicator.

$$\text{Equipment Criticality} = \text{Failure Frequency (/yr)} \times \text{Cost Consequence (\$)} = \text{Risk (\$/yr)}$$

The ‘cost consequence’ is the DAFT Costs. The ‘failure frequency’ is from the company’s maintenance history, or industry norms for a similar situation.

Standard equipment criticality is also used to rate equipment in priority order of importance to the continued operation of a facility. The equipment that stops production, or that causes major production costs when failed is considered most critical. Once the criticality is known the facility’s resources, engineering effort, operations practices, maintenance and training are matched to the priority and importance of the item’s continued operation. The Plant and Equipment Wellness approach to equipment criticality differs from the standard approach in that it uses DAFT Costs, and not production impact, to gauge the business risk of equipment failure. A key premise of Plant and Equipment Wellness is that we are building a world-class business. To make the right business decision it is necessary to know the business-wide losses and not simply the production losses of a failure. Unless the true and total business-wide costs are included in determining equipment criticality, the full risk of an equipment failure to the business is not recognised. Using DAFT Costing gives a more accurate value of consequential loss to the whole business and so a truer business risk is determined.

A competent team of people is drawn together to identify the equipment criticality for a facility. Normally a database of DAFT Costs is first developed. The database is used to populate calculation spreadsheets and makes the analysis quicker and easier. Typically the review group consists of the operators, maintainers and designers of the plant who contribute their knowledge and experience. The group reviews drawings of the facility’s processes and its equipment. Equipment by equipment they analyse the consequences of failure to the operation and develop a table showing each equipments criticality rating. It is the practice that the final arbiters of a choice are the Operations or Production Group, since they must live with the consequences and costs of a failure.

## Risk Matrix Calibration

The persons involved with the risk assessment need to –

- a. Understand the equipment operation and design – operator manuals, maintenance manuals and design drawings contain this information.
- b. Understand the impact on production of losing the equipment. The information is in plant drawings, Process Flow Diagrams (PFD), Process and Instrumentation Diagrams (P&ID).
- c. Know the business-wide financial loss from a forced outage. The DAFT Cost losses for a typical downtime period must be quantified.
- d. Know the effects on business reputation and the impact on Clients of forced outages.
- e. Review and adopt the risk control methodology in international risk management standards, such as Australian Standard 4360 – Risk Management, and its international equivalents.
- f. Calibrate the consequences on the Risk Matrix using the information developed from the above and the advice of experienced and senior persons in the operation under review.

## **Asset Assemblies and Components**

In order to understand the knock-on consequences of failed assemblies in individual equipment, each asset is subdivided into its major assemblies for separate risk analysis. If major assemblies contain substantial numbers of individual equipment, then these are further divided into sub-assemblies.

## **Risk Assessment**

The Risk Identification and Assessment Template of Table 8.4 is used to list the operating risks to each equipment, assembly and sub-assembly. Alternately, a spreadsheet is developed to replace the template. For equipment and assemblies under assessment use a calibrated Risk Matrix to categorise Consequence (1-5), Likelihood (1-6) and Risk Level (L, M, H, E) from each risk.

## **Risk Management**

For High and Extreme Risk Levels use the Risk Treatment Schedule and Action Plan Template of Table 8.5 to list actionable activities that will reduce risk by at least two levels. For Medium Risk Levels identify actions that will reduce them to Low. A Failure Mode and Effects Analysis or Reliability Growth Cause Analysis is used to identify required risk management activities to sufficiently lower the risk levels of individual parts.

## **Performing a Plant Wellness Equipment Criticality Analysis**

In keeping with the premise that we are building a world-class business, Plant Wellness requires that the chance of failure be prevented during the operating life of plant and equipment. To achieve that outcome, the Plant Wellness method again diverges from the standard method in its rating for equipment criticality. Plant Wellness equipment criticality envisions the worst outcomes (including plausible ‘acts of God’ like lightening and serious bad weather damage), death of employees, destruction of the environment and major plant and equipment loss if such consequences are plausible, especially if known to happen in the industry. The assumption of sure catastrophe makes the DAFT Cost the initial equipment criticality rating because the chance of failure is taken to be certain. The DAFT Cost and the catastrophic outcomes of the incident are the consequences used in the risk matrix to determine a risk level. Risk is then reduced by selecting mitigations that lower the frequency of an event to levels not expected to happen during the equipment’s working life. The frequency of failure is an outcome of a Plant Wellness equipment criticality analysis, not an input. Selecting responses that limit the consequences from a risk event is the secondary line of defence in Plant and Equipment Wellness. To do anything less than control the frequency of failure means a business is running on luck, and not on good judgement and sure risk management.

In many cases a failure event will not be acceptable under any circumstances (for example, if there was risk to human life, total or substantial production plant destruction, loss of a customer, or a catastrophic environmental incident). It is then unnecessary to ponder the frequency of the event because it is so horrific that everything justifiable to stop it is employed in its prevention. Even if such a failure were to happen once in one-hundred years, it would cause such severe effects that it must never happen.

It is impossible to predict when a one-in-ten year, or a one-in-twenty year, or a one-in-one-hundred year failure will occur. It could be tomorrow. Beware when standard risk analysis multiplies consequential cost by a low chance of the event occurring. The true devastating impact on the business is hidden by the low risk value. Catastrophic incidents do eventually

happen if not prevented. By first discounting major events because their frequency is low you are guaranteeing that, from time to time, catastrophes will happen in your operation. This is another example of misunderstanding the capability of a process that leads to decisions which destroy equipment and businesses. Failures are controlled by use of appropriate engineering design, construction controls, operational practices and maintenance methods, systems and practices, not by hoping they will not happen.

If an operation lives with many disastrous risks, the odds worsen with time that one or more will happen. As the years go by and a possible failure has not yet occurred, the chance of the event rises because protective systems degrade, uncontrolled modifications are made, management focus changes, experienced people are replaced by those less experienced, people become complacent, along with numerous other reasons that become the root causes of failure. Unless preventive precautions are vigilantly maintained the worst failure event will eventually occur. In an operation carrying many unaddressed low-chance, high-cost opportunities there will be a steady stream of catastrophes. The next one is just around the corner. By identifying equipment criticality as the worst DAFT Cost it highlights risks that would be considered minor by traditional rating methods and forces adoption of the necessary precautions to prevent them.

The full range of possible equipment failure scenarios is costed in order to provide complete understanding of all operational risks. Knowing the full risk profile for the equipment allows better design, operating and maintenance decisions to be made to manage those risks. The same method of analysis is also applied to rate the criticality of each assembly in the equipment, and can be continued to sub-assembly and parts failures if required; though the failure of parts is best analysed with Failure Mode Effect Analysis or Reliability Growth Cause Analysis.

### **Estimate the Size of Risk Reduction**

Many ideas to reduce risk have little real effect. The prevention strategies to limit chance of failure and the actions chosen to minimise the consequence of failure need to actually reduce risk to the required lesser levels. Estimating the extent of risk reduction can be done in a table, such as Table 8.6, or with a risk matrix. Provided mitigation significantly removes the stresses from equipment parts it is considered effective <sup>50</sup>. When parts are much less stressed and fatigued the frequency of failure falls and there are far fewer failure events. In order to accept that a suggested improvement is effective, it must be unquestionable in its ability to reduce stress levels and stress accumulation by a good margin from what would have been without it. Proof trials, such as reduced electrical power use, lowered equipment vibration levels, lesser operating temperatures, or other appropriate factors for monitoring, can be conducted on the equipment to confirm the stress reduction gained by a suggested mitigation. Team agreement is best when revising event frequency or likelihood, as a group decision that is well debated and discussed uses the ‘wisdom of crowds’ effect for arriving at consensus.

Gradually you build a documented engineering, maintenance and operational strategy to deliver highly reliable equipment. No longer is there mystery as to why maintenance is done, why plant is operated to reduce stress or why particular engineered solutions are required. The amount and type of engineering, operating and maintenance is matched the levels of risk willing to be carried by the operation.

### **The Problem with Standard Equipment Criticality Decision Methods**

The rating of an equipment item at a certain criticality is the result of subject matter experts making informed decisions about the frequency and consequences of a failure. These opinion-

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<sup>50</sup> Sherwin, David, Retired Maintenance and Reliability Professor, ‘Introduction to the Uses and Methods of Reliability Engineering with particular reference to Enterprise Asset Management and Maintenance’ Presentation, 2007.



based choices are open to misunderstanding and favoured choosing. Because mitigations involve subjective decisions based on past experience and the knowledge of consequences, it is possible that a person's knowledge is not deep and broad enough to make the better choice. They may be overly conservative and make an item a high criticality when it is not, thereby causing the maintenance costs to rise from unnecessary use of resources. Worst would be a choice that is a low criticality when it should be high and so chancing future failure.

In the Author's field experience, standard criticality rating is done too superficially to appreciate the real risk equipment failures cause a business. Important equipment gets mistakenly rated at a lesser risk than it should and so does not get sufficient and adequate maintenance and operator care. When a poor analysis is done the risk is not controlled well enough and the equipment continues to fail, much to people's wonder. But using DAFT Costing reduces the problem of subjective opinion, as knowing the full financial impact of failure encourages sound, fact-based decisions to be made.

In Table 8.7 is an example of a normal equipment criticality rating for a family car. It uses the traditional operational impact approach. Keeping the car in operation is important, but no consideration is given to the total effect on the family of a failure.

The standard methodology has produced maintenance and operating recommendations to address the perceived risks in use of the car. But there is no evidence that mitigations are correctly matched to the risk, or that they are adequate to control the risk to the family, because the real risks have not been quantified as a cost the family must suffer.

Table 8.8 shows a criticality rating for the family car which uses the Plant Wellness equipment criticality method. The analysis starts by identifying the DAFT Costs for a total failure of each major assembly and its main sub-assemblies. It is also useful to note the length of time taken to recover from an incident. Often the opportunity loss caused by the downtime is a more critical factor than the cost of repair. For this example the risk matrix of Table 8.3 is recalibrated at \$20 for 'Insignificant' and increasing in multiples of ten. The risk matrix is used to determine the risk rank and a total risk number. For example, the fuel system has a moderate cost of \$1,500 if it fails (nearest consequence value is 3), with a rare chance of failure (frequency value 2).

In the table there is a DAFT cost of \$20,000 for damage to the car body that is a substantial cost to its owner. It is also the highest risk number because road accidents are possible (frequency value 4). Damage to the chassis from road accidents or running over curbs comes next at \$15,000 to repair. Broken suspension cost of \$8,000 is third. The engine at \$6,000 is not the most expensive failure, but there is an annoying time delay in getting the car back on the road if key engine components are damaged. The standard equipment criticality rating would not have produced such a thorough understand of the failure consequences to the organisation (a family in this example). Having a real cost of failure provides greater insight into the full impact of a risk. The biggest risks are from car accidents and uncaring drivers who do not respect the vehicle. The best strategy to minimise risk is to ensure drivers have high driving skills, along with good road sense and attitudes. They could be sent to a defensive driving school to learn accident evasion techniques. The mechanical and electrical equipment in the car is best protected from failure by good driver education of how a car and its parts work, along with regular servicing and inspection. The service organisation will need to do a wide range of inspections and the selection of the service provider is based first on how comprehensive and competent is the service they offer, followed by their cost.

Using DAFT Cost shows that the failure cost of parts not considered important by the standard equipment criticality rating methods is actually very high. These parts received little attention in the standard criticality rating method because a low frequency implies few failures. People consider them a lower importance because of their supposedly low risk. The



*Table 8.6 – Equipment Risk Reduction Spreadsheet Layout.*

Ref No	Equip Tag No	Equip Desc	Failure Event or Causes	Original Estimated Inherent Risk (\$/Yr)	Engineering, Maintenance and Operational Activities to Reduce Risk	Years Equip Remaining in Service or Expected to be in Service	Current No of Historic Failure Events due to Cause (/ Yr)	No of Failure Events or Expected due to Cause after Risk Reduction	Annualised Likelihood of Failure Event after Risk Reduced (/ Yr)	DAFT Cost of Failure Event (\$)	Revised Inherent Risk (\$/Yr)
1	2	3	4	5	6	7	8	9	10	11	12

*Table 8.7 – A Traditional Equipment Priority Analysis for a Motor Car.*

Priority Rating for a Rear Drive Family Motor Car						
Component	Sub-Components	Failure Effects			Criticality by Risk	Maintenance & Care Required
		Unusable	Causes Difficulty	No Concern		
Engine						
	Fuel system	Y			High	Regular service
	Crank and pistons	Y			High	Regular service
	Engine block	Y			High	Regular service
	Cooling system	Y			High	Regular service
	Oil system	Y			High	Regular service
	Ignition system	Y			High	Regular service
Gearbox						
	Input shaft	Y			High	Regular service
	Internal gears	Y			High	Regular service
	Output shaft	Y			High	Regular service
	Casing	Y			High	Regular Inspection
Drive Train						
	Drive shaft	Y			High	Regular Inspection
	Differential	Y			High	Regular service
	Axels	Y			High	Regular Inspection
	Wheels		Y		Medium	Regular Inspection and rotation
Body						
	Dash display		Y		Medium	Regular Inspection
	Indicator lights		Y		Medium	Regular Inspection
	Lights		Y		Medium	Regular Inspection
	Windows		Y		Medium	Regular Inspection
	Doors		Y		Medium	Regular Inspection
	Panels			Y	Low	
	Chassis		Y		Medium	Regular Inspection
Suspension						
	Shock absorbers	Y			High	Replace at end of life
	Springs	Y			High	Replace at end of life
	Frame		Y		Medium	Regular Inspection

Table 8.8 – Plant and Equipment Wellness Criticality Analysis for a Motor Car.

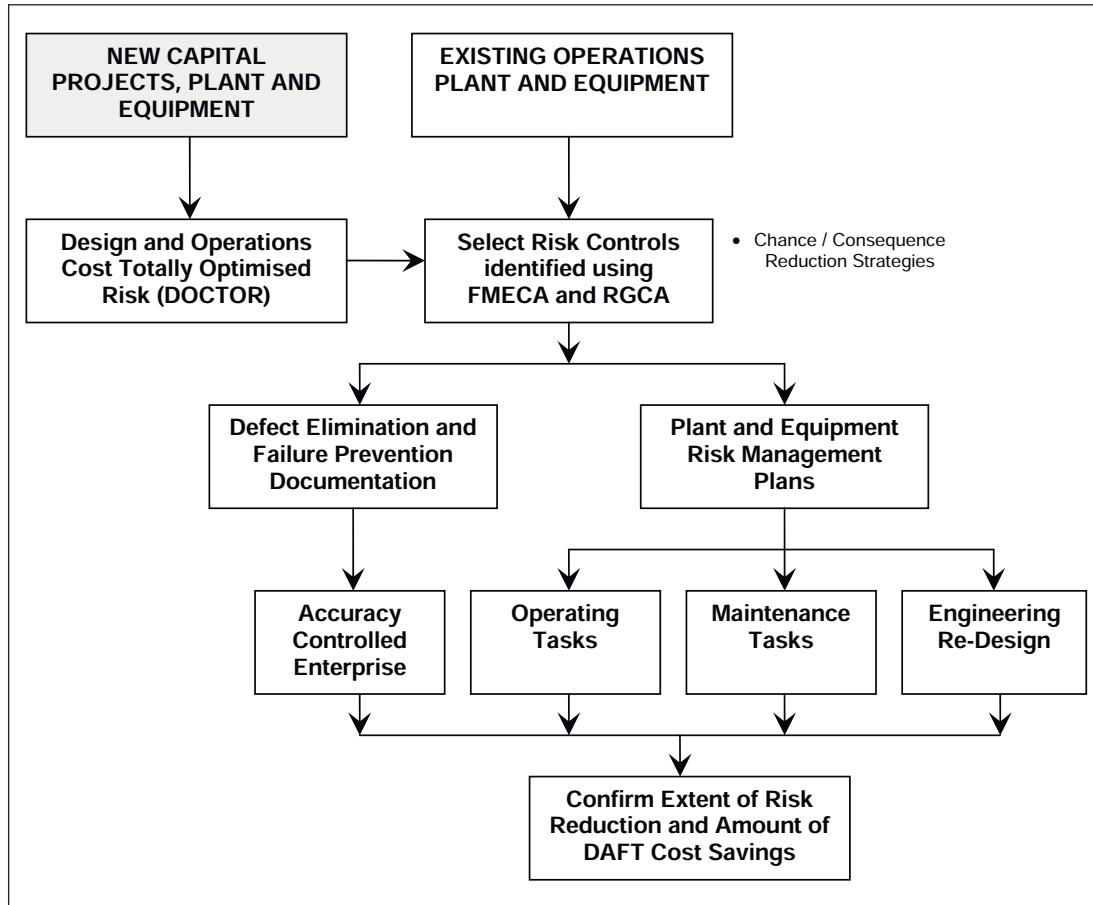
Component	Sub-Component	DAFT Cost Rating			Criticality By Risk		Criticality by DAFT Cost	Required Operating Practice	Required Maintenance
		System Loss Cost \$	Assembly Loss Cost \$	Time to Recover Days	Rank	Number			
Engine		6000		21	Medium	6	6000		
	Fuel system		1500	3	Medium	5	1500	Monitor operation	Regular service of parts
	Crank and pistons		3000	21	Medium	5	3000	Monitor operation	Replace at end of life
	Engine block		3500	21	Medium	5	3500	Monitor operation	Replace at end of life
	Cooling system		1500	5	Low	5	1500	Monitor operation	Regular service of parts
	Oil system		1000	5	Low	5	1000	Monitor operation	Regular service of parts
	Ignition system		1500	5	Low	6	1500	Monitor operation	Regular service of parts
Gearbox		5000		28	Medium	5	5000		
	Input shaft		1000	5	Low	4	1000		Regular service of parts
	Internal gears		2500	28	Low	4	2500		Regular service of parts
	Output shaft		1500	5	Low	4	1500		Regular service of parts
	Casing		3000	28	Low	4	3000	Monitor operation	Regular Inspection
Drive Train		2500		28	Medium	7	2500		
	Drive shaft		1000	14	Low	4	1000	Monitor operation	Regular Inspection
	Differential		2500	28	Medium	5	2500		Regular service of parts
	Axel x 1		1500	14	Low	4	1000		Regular Inspection
	Wheel x 1		1000	3	Medium	5	1000	Monitor operation	Regular Inspection
Car Body		20000		54	High	8	20000		
	Dash display		4000	28	Medium	5	4000	Monitor operation	Regular Inspection of condition
	Electrical system		4000	14	Medium	6	4000	Monitor operation	Regular Inspection
	Lights		1000	5	Medium	6	1000	Monitor operation	Regular Test
	Window x 1		1000	5	Medium	6	1000	High driving skills	Regular Inspection
	Door x 1		2000	14	Medium	6	2000	High driving skills	Regular Inspection for corrosion
	Panel x 1		3000	14	Medium	6	3000	High driving skills	
	Chassis		15000	54	High	7	15000	High driving skills	Regular Inspection for corrosion
Suspension		8000		28	Medium	5	8000		
	Shock absorbers		1000	3	Medium	4	1000	Monitor operation	Replace at end of life
	Springs		1000	5	Medium	3	1000	Monitor operation	Replace at end of life
	Assembly x 2		5000	28	Medium	5	5000	High driving skills	Regular Inspection for damage

DAFT Cost approach warns that though the equipment may not fail often, when it does it will be expensive and have destructive consequences for the owner. By reviewing the cost of failure independently of the chance of the failure, the DAFT Cost equipment criticality approach makes clear how bad each failure would be unless prevented from happening.

The Plant Wellness equipment criticality process also determines where responsibility lays for protecting equipment from harm. From the type of failure it is clear if the operator or maintainer needs to conduct mitigation. Management of the risk by proper operation, or by proper maintenance, or by re-engineering becomes self-evident. For the car only the driver (the operator) can prevent an accident. Only the driver can steer the car so it does not go over a curb and destroy the suspension. The maintainer cannot prevent such failures. Only for preventive maintenance or after equipment damage is the maintainer involved. The family car risk management plan involves having a skilled operator (the driver) who knows how to drive well and does not put the car into situations risking damage. Regular servicing of the car and its systems are important, as is the driver noticing when things are not working properly and reporting them for rectification before failure.

Knowing the full and real cost of a failure can help validate additional training, the purchase of new test equipment and changes to procedures not justifiable with traditional equipment criticality rating methods that under value risk.

## PROCESS 3 – Select Operating Risk Controls



## **Description of Process 3 – Selecting Risk Control Strategy**

The risk control strategies chosen are critical to minimising operating costs and creating equipment reliability. Doing maintenance that does not reduce risk is pointless. Doing maintenance because of poor design and selection means carrying unnecessary operating costs. It is essential to apply a methodology to review operating costs imposed by design choices and pick good operating options in capital projects. When doing new capital project or plant upgrades the Design and Operations Costs Totally Optimised Risk (DOCTOR) methodology minimises future operating costs. It may not be possible to cut every operating cost, but the DOCTOR will make people look at how to reduce operating risk before making the final equipment and design choices.

### **Select Risk Control Options:**

Operating plants that 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 limits risk 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.

### **Select Risk Control Actions identified using FMECA and RGCA:**

Go deep into the detail of what causes equipment failures in your operation. Find and understand the failure mechanisms in order to select the ideal solution for the root causes. Identify all possible failures using the FMECA and Root Cause Growth Analysis (RCGA) spreadsheets provided in the CD accompanying this book.

### **Chance and Consequence Reduction:**

Chance reduction is proactive risk removal strategy. Chance reduction removes the possibility of failure. Chance reduction leads to world-class operations performance and least costs. Consequence reduction accepts that failure will happen and minimises its impact. Consequence reduction can never lead to least operating costs. Consequence reduction is the strategy of last resort. Companies do it because they think it is adequate and it looks like a cheap option. It never is on both counts. Only chance reduction leads to least operating costs and maximum uptime. In the Risk Control Plan Spreadsheet provided in the CD accompanying this book write the chance reduction controls that prevent failure incidents arising. For those that cannot be prevented write the consequence reduction actions to contain the losses.

### **Defect Elimination and Failure Prevention Documentation:**

As part of risk control, list the documents and standards to write to prevent the defects that cause failures from entering your operation.

### **Plant and Equipment Risk Management Strategy:**

Select the operating, maintenance, re-engineering and defect elimination strategies you will use.

### **Confirm Extent of Risk Reduction:**

Check the proposed strategies remove, or at least substantially reduce the risk of each failure.

## 9. Use Process Maps to Identify Risk and Improve Reliability

A Process Map for a piece of equipment or a job allows use of reliability improvement principles to reduce the chance of failure. In Chapter 1 the reliability of series processes was explained. We found that series process reliability is improved by introducing parallel requirements for each step of the process. Once a process map shows all process steps we can investigate how to include parallel activities to increase each step's reliability. Better still would be to remove the step or find ways to error proof it so that nothing can go wrong.

Series reliability improvement revolves around applying the three Reliability Properties of Series Processes and building parallel arrangements to cause higher reliability. The three series reliability properties are repeated below.

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

Reliability Property 1 means that anyone who wants high series process reliability must ensure every step in the series is highly reliable.

- **Add 'k' more items into a series system of items, and the probability of failure of all items must fall an equal proportion to maintain original system reliability.**

Reliability Property 2 means that if you want highly reliable series processes you must remove as many steps from the process as possible. Reliability Property 2 says to simplify, simplify, simplify!

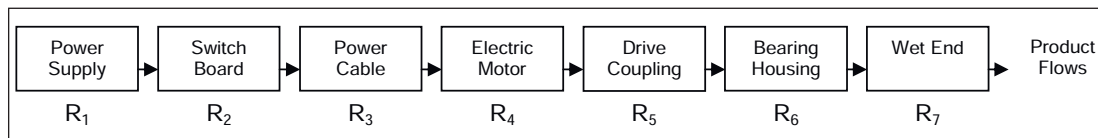
- **A small rise in reliability of all items causes a larger rise in system reliability.**

Reliability Property 3 means that system-wide reliability improvements pay off far more than individual step by step reliability improvements.

These three properties, and the paralleling of process steps, can be applied to reduce the risks in using operating equipment and in doing jobs. You can design the equipment reliability that you want by using processes with the practices and methods that deliver it.

### Apply Series System Reliability Property 1

Figure 9.1 is a high level process map for a centrifugal pump-set when in operation. We will use the process map to design reliability improvements.



*Figure 9.1 – A Centrifugal Pump-set Process Map.*

We start by applying Series Process Reliability Property 1 – The reliability of a series system is no more reliable than its least reliable component. We need to identify the reliability of each assembly so that we can find the least reliable ones and see if they need improving. For the sake of the example select a minimum series reliability of 0.9999. This is the chance of 1 failure in 10,000 opportunities to have a failure, which is what would be expected from quality equipment. For a pump-set that runs say ten times a day it represents 1000 days, about three years, without a failure. To get that requirement from the pump-set, each of its assemblies needs a greater reliability. We can estimate the scale of the reliability required by using Equation 1.1 and assuming that all parts have equal reliability.

$$R_{\text{pump-set}} = R_1 \times R_2 \times R_3 \times R_4 \times R_5 \times R_6 \times R_7 = R_n^7 = 0.9999$$

$$R_{\text{pump-set}} = 0.99998571^7 = 0.9999$$

This is an individual assembly reliability of 0.99998571, or about 14 failures in every 1,000,000 opportunities for failure. In other words, each assembly can only have the chance of one failure every twenty years in order that the pump-set has the chance of only one failure in three years. One failure in twenty years is a very high reliability requirement for some assemblies in the pump-set, like the drive coupling and mechanical seal, but not impossible for many of the other parts. For the shaft drive coupling and mechanical seal it is not difficult to find dozens of reasons that cause them to fail sooner than once in twenty years. These include incorrect bore tolerances, shaft misalignment, torque overload, poor assembly on installation, corrosion, wear and impact, chemical decomposition of elastomeric items, along with many other common failure causes.

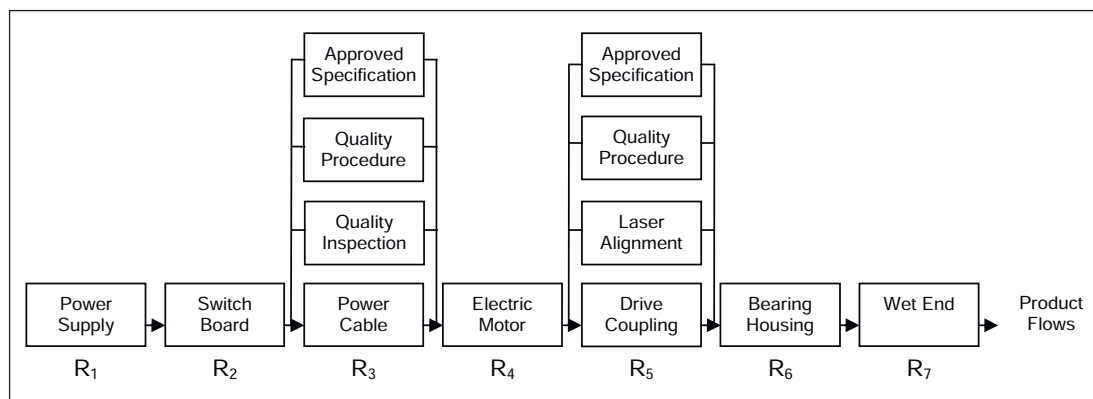


Figure 9.2 – Centrifugal Pump-set Reliability Improved by Parallel Tasks.

The power cabling is an example of an item with high reliability designed into it. Lugs crimp the cable wires at both ends. The cable enters into the switchboard and motor starter through gland connections. The lugs bolt to connections in a particular way to ensure firm contact so that hot-spots do not develop. Though early-life electrical failures from poor workmanship has occurred, better than twenty years of failure-free service is normally expected from industrial power supply systems. By using good methods and practices for cabling and connections, combined with good quality control, it is possible to get fewer failures than the one in twenty year opportunity required for our pump. The electrical components can deliver the required reliability by using installation best practices done with care. However, mechanically it is very unlikely that this pump-set will achieve the reliability required. Unless there are better solutions to prevent environmental degradation and mechanical stress the parts cannot last 20 years failure-free. This is where the process maps help us to identify more reliable options than those now used.

Figure 9.2 shows the tasks and requirements added in parallel on the cabling and drive coupling, that, if done correctly, will greatly improve the reliability of each step. For the coupling the added parallel tasks are to purchase it using an approved engineering specification that addresses all likely modes of failure, install it using quality work procedure that prevent deformation, and laser align shafts to precision standards. Do all these and the failure-free life of the coupling is greatly enhanced. The process map helps us to specify parallel tasks that will improve the step reliability.

### Apply Series System Reliability Property 2

The second Series System Reliability Property – add ‘k’ more items into a series system of items, and the probability of failure of all items must fall an equal proportion to maintain



original system reliability – requires us to ask if we can remove unnecessary components from the system. By removing items or steps the system is more reliable because there are fewer things to go wrong.

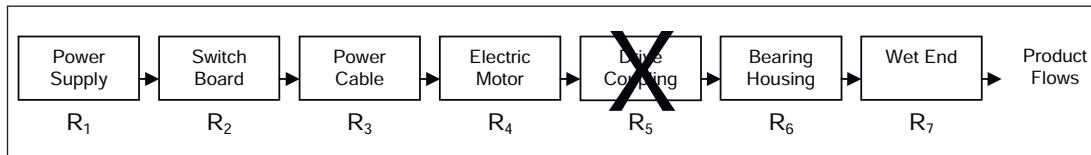


Figure 9.3 – Centrifugal Pump-set Reliability Improved by Removing Coupling.

Figure 9.3 asks what would happen if we remove the drive coupling, one of the highest risk assemblies, from the centrifugal pump-set. Is there technology to eliminate the need of a coupling? Figures 9.4 and 9.5 show two such technologies – canned motor pumps and magnetic drive pumps.



Figure 9.4 – Canned Motor Pump.



Figure 9.5 – Magnetic Drive Pump.

Both these pumps do not have a shaft drive coupling. With one assembly removed, the system reliability (assuming the other items keep the same individual reliability) becomes:

$$R_{\text{pump-set}} = R_1 \times R_2 \times R_3 \times R_4 \times \text{X} \times R_6 \times R_7 = R_n^6 = 0.9999$$

This calculates to individual assembly reliability of 0.99998333, which equates to no more than 17 failures in every 1,000,000 opportunities for failure. It is a minor reduction in assembly reliability from the 14 failures in 1,000,000 opportunities of a coupled pump-set. What this small reliability reduction tells us is that equipment reliability is difficult to improve if good quality parts and assemblies are already used. To confirm that simplifying a system of good quality parts produces only small change in system reliability, let us remove the bearing house as well as the coupling. The system reliability then becomes:

$$R_{\text{pump-set}} = R_1 \times R_2 \times R_3 \times R_4 \times \text{X} \times \text{X} \times R_7 = R_n^5 = 0.9999$$

The individual assembly reliabilities are 0.99998. We now only need assemblies with 20 failures in every 1,000,000 opportunities to give our imaginary 5-assembly pump-set a chance of one failure in three years. Even after simplifying from seven to five items, we achieve the same system reliability with only marginally lesser reliable assemblies. If you are already using quality components made with quality materials and quality manufacturing then you must look for improved equipment reliability in other ways. Unless your plant and equipment is full of poor quality parts and assemblies, the equipment is probably not the cause of your failures.

### Apply Series System Reliability Property 3

The third Series System Reliability Property – a small rise in reliability of all items causes a larger rise in system reliability – is the final perspective to consider. Figure 9.6 shows the introduction of precision work procedures to exacting stress-reducing specifications for each assembly. These procedures do not involve changes to components; rather they are learned skills and practices used company-wide. Precision skills, where work is done to precise standards that prevent stress being introduced, causes the reliability of the equipment to lift. By paralleling precision skills with high work accuracy for every item in the system we get greater system reliability. Parallel system reliability is calculated with Equation 1.2, repeated below.

$$R_{\text{para}} = 1 - [(1-R_1) \times (1-R_2) \times \dots (1-R_n)]$$

Values for human error rates in a variety of work situations are available<sup>51</sup>. Task error rates of 1 in 100 are a reasonable estimate for work done with precision to quality standards, combined with proof-testing for confirmation. To retain system reliability of 0.9999, the reliability of each paralleled arrangement, assuming they are identical, is calculated from:

$$R_{\text{pump-set}} = 0.9999 = R_{1\text{para}} \times R_{2\text{para}} \times R_{3\text{para}} \times R_{4\text{para}} \times R_{5\text{para}} \times R_{6\text{para}} \times R_{7\text{para}} = 0.99998571^7$$

We can calculate the reliability of each parallel arrangement, assuming identical reliability:

$$R_{\text{para1}} = 1 - [(1-R_{1A}) \times (1-0.99)] = 0.99998571$$

$$R_{1A} = R_{2A} = R_{3A} = R_{4A} = R_{5A} = R_{6A} = R_{7A} = 0.9986$$

That is interesting: prior to precision workmanship we needed assembly reliabilities of 14 failures per 1,000,000 opportunities to get pump-set reliability of 1 failure in 10,000 opportunities. With precision work, proof-tested to meet stress-reducing quality standards, we can get the same system reliability by using equipment with 1400 failures per million opportunities.

In poorly skilled operations buy top quality machines. In operations practicing precision maintenance and operation you can use machines of lower quality because they will be improved. If you want the very best reliability results, use quality equipment maintained to precision quality standards.

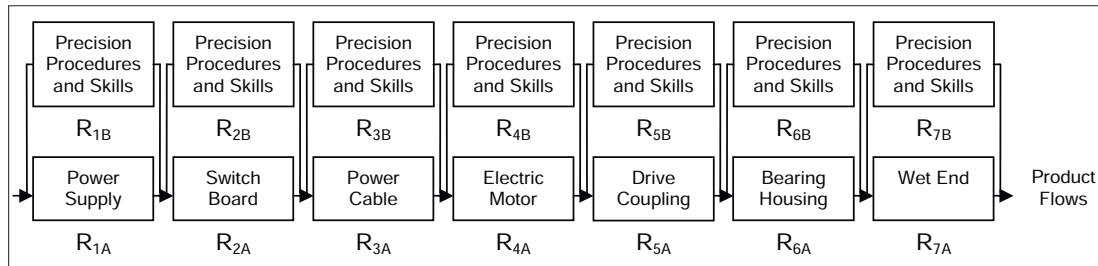


Figure 9.6 – Pump-set Reliability Improved by Parallel Precision ACE 3T Activities.

<sup>51</sup> Smith, Dr, David J., Reliability, Maintainability and Risk, Seventh Edition, Appendix 6. Elsevier, 2005.

## 10. Failure Mode Effects and Criticality Analysis

Because parts fail first and then equipment stops, an effective equipment risk reduction strategy requires a detailed analysis of the causes of parts failure. This can be done with Failure Mode Effects and Criticality Analysis (FMECA)<sup>52</sup>, or the deeply thorough Reliability Growth Cause Analysis. As a minimum, the simpler Failure Mode Effects Analysis (FMEA) is used when criticality is not required. In an FMECA the failures identified by the FMEA portion of the method are further classified by their risk severity.

Failure Mode Effects and Criticality Analysis is both a qualitative and quantitative technique providing indication of the nature of a risk and its size. The approach involves documenting the findings of a detailed design review on the failures inherent in the design of an equipment item. It permits identifying how equipment parts can fail and lets you recognise when to design-out a failure, or apply suitable maintenance and operating practices to prevent a failure. Table 10.1 lists the meaning of words and terms used in FMECA/FMEA.

*Table 10.1 – FMECA/FMEA Terms and Definitions.*

Term	Definition
Failure	Any unwanted or disappointing behaviour of an item
Failure Mode	How a part, or combination of parts, fails. 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 or Cause	The processes by which the failure modes arose. It includes physical, mechanical, electrical, chemical, or other processes and their combinations. Knowledge of a failure mechanism provides insight into the conditions that cause failures
Failure Site	The physical location where the failure mechanism is observed to occur, and is often the location of the highest stresses and lowest strengths
Failure mode	Effect of the immediate consequence on the use of the item
Criticality	Combines Severity (a measure of cost and inconvenience of the failure) and Frequency (how often mode(s) that cause a failure arise) to indicate the risk caused by the item should it fail
Critical Item	Is a part or assembly where the failure mode(s) remains and has not been designed-out. These items require operating and maintenance strategies to ensure a long trouble-free life
FMECA Report	A document that explains why known modes of failure occur. It becomes the basis to decide the maintenance strategy for a part or assembly

There are two levels at which the FMECA/FMEA can be conducted. One is to look at the loss of the equipment to identify what failures would cause that to happen. This is the Functional Approach, and has some commonality with Reliability Centred Maintenance. The second method is to look at each part and identify what would happen if it failed and how the failure could be caused. This is the Hardware Approach. The second approach is the more thorough, though requiring more time. It is required by the Plant and Equipment Wellness methodology.

<sup>52</sup> Sherwin, David., Retired Maintenance and Reliability Professor, 'Introduction to the Uses and Methods of Reliability Engineering with particular reference to Enterprise Asset Management and Maintenance' Presentation, 2007.

The Criticality portion of FMECA is typically a mathematical calculation of the probability of the failure occurring<sup>53, 54</sup>. A concern in using formulaic criticality values is they are unlikely to be right. Both the chance of a situation arising exactly as imagined, and of producing the cost consequences expected, is highly variable. The actual risk depends on the circumstances present at the time and the nature of the situation. The Severity and Frequency used to calculate Criticality can only ever be guesses, which means the resultant is an even bigger guess. Because the probability calculations are difficult and the results may be misleading anyway, Plant and Equipment Wellness rates criticality with the risk matrix method of Chapter 8 – Operating Equipment Risk Assessment. It assumes certain failure, and the risk level (a measure of criticality) is determined using the resulting DAFT Cost and business consequences. Mitigation is then selected to reduce the frequency to a level unlikely to happen during the operating life of the equipment. An FMEA is used to determine the parts failures that stop equipment.

### **Failure Mode and Effects Analysis**

When traditional Criticality is not included in the analysis it becomes a Failure Mode and Effects Analysis. A table is used to review each assembly and its parts for the many ways they can fail. Table 10.2 is a sample of the Plant Wellness FMEA worksheet layout.

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 used during design the principle is to consider each mode of failure of each part and determine the knock-on and system-wide effects in-turn. The learning from the FMEA is put back into the design and the equipment is improved. Specific risk management requirements can also be 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.

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 failure mode(s) and causes.

### **Performing a Failure Mode and Effects Analysis**

1. Start by specifying the purpose of the FMEA. It can be for reasons of safety, reliability improvement, plant availability, repair cost, mission success, etc. to align attendees' viewpoints.

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<sup>53</sup> MIL-STD 1629 , 'Procedures for Performing a Failure Mode, Effects and Criticality Analysis'.

<sup>54</sup> BS5760 Part 5, Reliability of systems, equipment and components. Guide to failure modes, effects and criticality analysis (FMEA and FMECA).

Table 10.2 – Plant and Equipment Wellness Failure Mode and Effects Analysis Worksheet Layout.

System: _____ Equipment: _____ Drawing: _____				<b>FAILURE MODE and EFFECTS ANALYSIS WORKSHEET</b>					Date: _____ Sheet: _____ of _____ Compiled By: _____ Approved: _____			
ID No.	Item Description	Function	Failure Modes	Failure Causes	At What Stage of Operation	Failure Effects			Symptoms prior Failure	Failure Detection Method	Rectification on Failure	Corrective Action to Prevent
						The Item	Neighbours	System				

2. Assemble a cross-functional team of people competent in the equipment to conduct the FMEA.
3. Provide all available design data and operating data to allow development of a full understanding of the equipment design and its service.
  - a. Each equipment asset and its assemblies need to be identified down to the part numbers on the bill of materials (BOM).
  - b. The equipment operation and design must be well understood by the people doing the FMEA.
  - c. The process conditions impacting the equipment and its components must be well understood by the people doing the FMEA.
4. Develop a process map of how the equipment operates (known as a functional block diagram).
5. Prepare the FMEA worksheet listing assemblies and components.

Put the team into a quiet, spacious room to work. Record results directly into a computer spreadsheets, or a large sheet of paper at least A3 size. Use a reference number for each failure mode to differentiate it from others. Write plentiful and clear descriptions – words are more important than numbers. Record the decisions made and the follow-up actions to be taken. On the process maps use historic records of failure to show those items that have failed, the failure frequency and all known failure causes. Include a remarks column to pass-on advice and knowledge to others so they do not unnecessarily repeat the work.

Complete the FMEA for all parts/component in all equipment using the FMECA spreadsheet on the CD accompanying this book. Column by column in the spreadsheet the team enters the required information and develops a thorough understanding of how parts can fail in service. For those items with stresses that are not significantly reduced, consequence reduction strategies are used to limit loss and downtime. The review team selects appropriate condition monitoring to ensure initiated failures are caught before they cause unplanned downtime, wastage and loss. It is wise to confirm risk is reduced significantly for parts to ensure that there will be fewer failures.

Performing a parts hardware level FMEA may appear to be a lot of work. The driving premise of Plant Wellness is to achieve low-stress conditions that eliminate all part failures during equipment working life. Understanding how that can be done requires analysis of the causes of a part's stress and to identify practical measures to prevent failure. Fortunately, once a part has been through an FMEA review the results do not change greatly for other parts of that type. Once a roller bearing, or an alternating current electrical power supply, or a ball valve have been through an FMEA, the same analysis will likely apply to the next roller bearing, alternating current electrical power supply or a ball valve. The review team simply re-examines the previous FMEA to confirm its relevance and includes any changes and additions applicable to the risks in the situation being investigated.

### **Developing a Risk Control Plan**

The FMEA process requires decisions on equipment design, maintenance and operation to reduce the level of risk a part carries. These decisions lead to actions that lower the frequency of an event and reduce its consequences. Each failure identified is addressed one-by-one until the risk control plan is complete. The risk control plan covers all that will be done, or not done, to remove or significantly reduce risk. It lists the mix of design, operating and maintenance activities that will lower equipment risk and deliver high operational reliability. Figure 10.1 shows where FMEA sits in the process of choosing risk management actions and the output it produces. Mitigation and prevention actions will fall to the Maintenance and Operations groups and design improvements will go to Engineering to do. Design-out is best done by a professional engineer or competent technical person who fully understands the equipment's purpose and design.

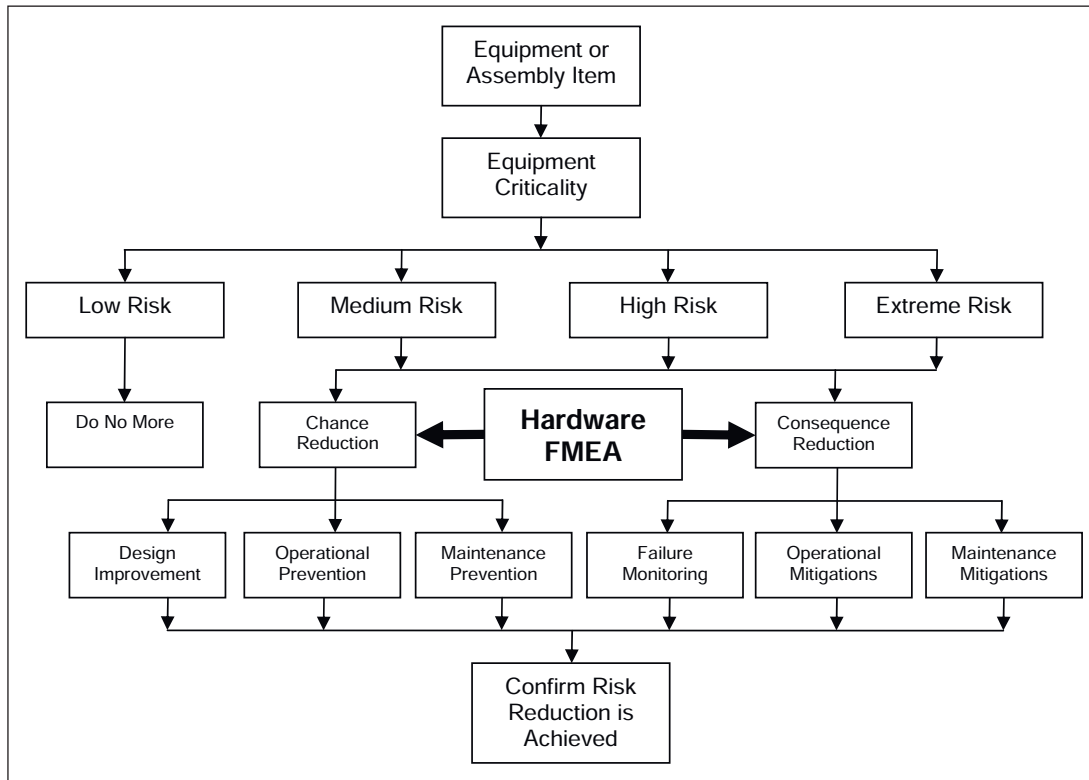


Figure 10.1 – Risk Management Strategy Selection Chart.

### Maintenance Tasks, Condition Monitoring, Critical Spares

From the FMEA are developed the required operating and maintenance procedures, the specific spares holding needed, condition monitoring inspections, preventive maintenance, replacement policy (i.e. replace with new on failure, or at near end-of-life), or breakdown strategies to use for each part. Reliability can only be improved if parts are not allowed to fail and doing the FMEA at parts level identifies the engineering, operational and maintenance issues that should be addressed for maximum component reliability.

The choices available to prevent equipment failure are:

1. Placing operating limitations on distressed parts (e.g. De-rating, Over-sizing, Precision Operation)
2. Changing the design to prevent parts overstressing (Design Engineering, Design-out Maintenance)
3. Remove the situations that lead to the failure (e.g. Defect Elimination, Precision Maintenance)
4. Monitor for the failure mode to detect its onset (e.g. Predictive Maintenance, Condition Monitor)
5. Replace parts before failure (e.g. Preventive Maintenance, Age-based Renewal, Shutdown Maintenance, Overhaul)
6. Control the environmental conditions causing failure to arise (e.g. Failure Prevention, Accuracy Controlled Enterprise).



It is necessary to only hold equipment spares to the level of equipment that is replaced. For example, if a pump wet-end was to fail and the best economic decision is to replace the entire wet-end with a new one and get the old one overhauled, you would only carry spare wet-ends and not also the individual parts for the wet-end. To proactively prevent the wet-end failing you need to know how each of its parts can fail and act to prevent the failures from happening. That is where a parts-level FMEA helps you greatly.

### **Work Procedures and Resources Requirements**

Risk reduction strategies are applied throughout the life cycle. The material selection and stress reduction choices made at design are the most effective in reducing risk. During manufacture, precision and work quality is crucial. On installation, again precision and work quality is vital to prevent distortion. During operation, low-stress operating practices are the best. When parts are stored, apply good stores management practices that retain their reliability. During maintenance, stipulate precision and quality workmanship with Accuracy Controlled Enterprise 3T procedures.

As a means to prevent parts' failures and control risk, numerous work activities involving condition monitoring, inspections, preventive maintenance and replacement of end-of-life parts will be identified in the FMEA and the equipment criticality risk analysis. Each of these operating and maintenance activities requires a documented Accuracy Controlled Enterprise 3T procedure (as explained in Chapter 14 – The Accuracy Controlled Enterprise) for performing the work to ensure the appropriate tasks are done correctly.

Included in the development of each procedure is an accurate estimate of the resources needed to do the work, the length of time they are needed, along with the parts to do the job. Once ACE 3T work procedures are written to cover a part's risk control activities, a job schedule for the year is developed. The schedule allows identification of the trade skills, the manning levels and materials needed to provide the risk management required. This information is also used for budgets and maintenance planning.

### **Turn the Plan into Procedures and Actions**

Once developed, the plan needs approval by all key stakeholders affected. Typically, these people are the Operations and Maintenance Department Managers and Work Team Supervisors. They need to review the plan and include anything else they feel is necessary. Ideally the Team Supervisors are in the FMEA review team so they understand the purpose of the review, and support the efforts needed to instigate and perform the risk control activities that arise. It will be wise to also organise meetings with other relevant managers and workplace groups to explain and discuss the resulting plans and the roles each person plays in their achievement.

Providing avenues of communication and opportunity for discussion helps gather support from the people who will implement the necessary strategies. It is only by doing the plan that it delivers results. The plan is actioned by introducing the necessary changes and practices into the workplace. Maintenance procedures will detail the breakdown, preventive, predictive and precision maintenance activities that will control the level of risk in the operation. They ensure that the environment for the parts is healthy and the stress levels are low. The design activities incorporate the failure prevention, defect elimination and design-out tasks that prevent failures. The operations group procedures will contain activities that control variation in the use of operating equipment and deliver stable operation below parts threshold stress levels. In this way each business group limits and reduces equipment risk by respecting the Physics of Failure limits.

## 11. Chance Reduction Risk Management

For interrogating its secrets, it is better to write the risk equation as:

$$\text{Risk} = \text{Chance} \times \text{Consequence}$$

The word ‘chance’ explains risk better than using ‘frequency’. Chance are the odds of an outcome: a 25% chance the next card will be a spade in a pack of poker cards, a 30% chance of rain on a cloudy day. Chance has the connotation of uncertainty, of unpredictability. It implies that we do not know when an event occurs. It reflects the real world much more truthfully than does the word ‘frequency’. Chance warns us that a once-in-five-year event can happen at any time; it provides a clearer connotation of risk.

Chance events require opportune occurrences to coincide. Accidents do not happen by accident. They need several enabling factors to exist together. A bad incident occurs when several unconnected factors align in such a way that the incident becomes possible. When the factors align there is opportunity for disaster. For a fire to start there must be fuel, air and an ignition source. All three must happen together. The Titanic Disaster (Example E11.1) is a famous case of consequent factors aligning to produce an accident.

Reduce the chance of an event occurring and you reduce the risk. Stop the necessary requirements for an incident to happen and the incident cannot occur. The use of ‘chance reduction techniques’ is the prime principle of risk control in the Plant Wellness Methodology. Risk can also be reduced by decreasing the consequences of an incident. That is the purpose of such things as emergency plans, fire brigades and ambulances. If we react quickly, correctly, and early enough, the consequences can be reduced. The use of consequence reduction techniques is a second level risk control principle in Plant Wellness.

In the risk equation the two factors, chance and consequence, are multiplied together. It would seem that the impact of either factor has equal effect on the risk. Halving the chance is equally as good as halving the consequences. Unfortunately most organisations fall into this trap. They think that it does not matter how they reduce their risk because either path produces the same result. It is not true. In reality the two ‘paths’ to reducing risk have totally different impacts on the prosperity of an organisation. The application of basic accountancy is sufficient to explain why the best path to take in risk management is to reduce the ‘chance’ of failure, and not its ‘consequence’.

### Impact of Risk Management Strategy

By individually applying chance reduction and consequence reduction to the basic business model we can identify their financial effect on the operation.

Figure 11.1 is the ‘death of many cuts’ production model encountered in Chapter 4. Each breakdown causes production time loss and a business-wide cost surge. Companies that use consequence reduction strategies minimise their losses by learning to fix breakdowns quickly. You do that by holding lots of spare parts in-store, setting-up a cache of parts by machines, training your repair people to fix things speedily or improving the equipment maintainability to do repairs faster. Figure 11.2 reflects the reduced production time loss when repairs are done rapidly. Comparing Figures 11.1 and 11.2 graphically shows that reducing the downtime produces profit improvement. Losses are less if the plant gets back into production quickly. Consequence reduction strategies do reduce risk.

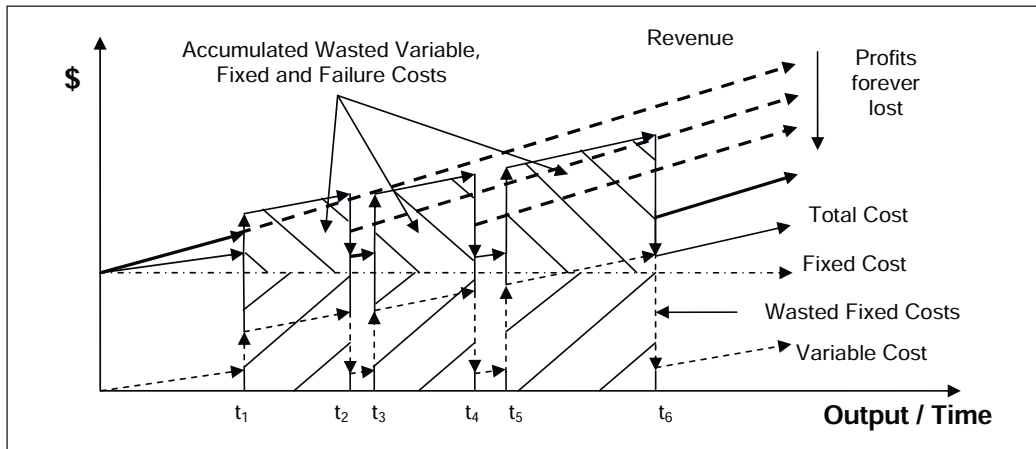


Figure 11.1 – Effects on Profitability of Repeated Failure Incidents (*Death of Many Cuts*).

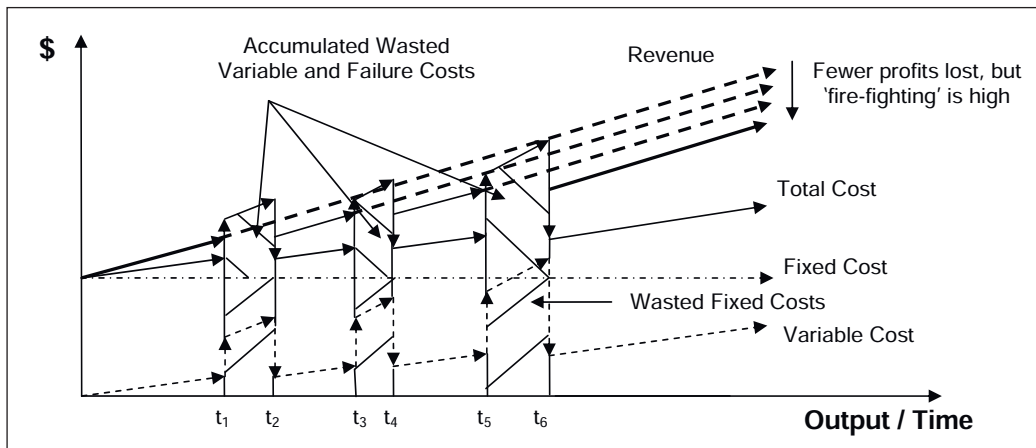


Figure 11.2 – Effects on Profit by Reducing Consequence Only.

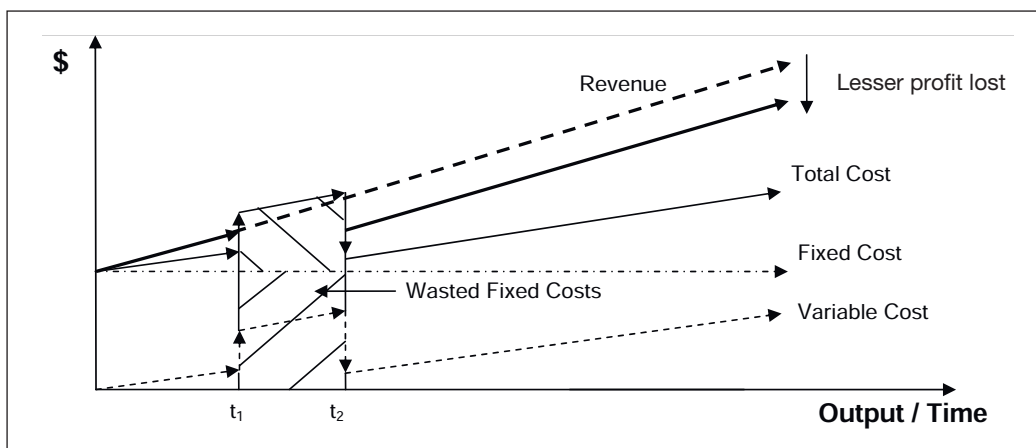


Figure 11.3 – Effects on Profit by Reducing Chance Only.

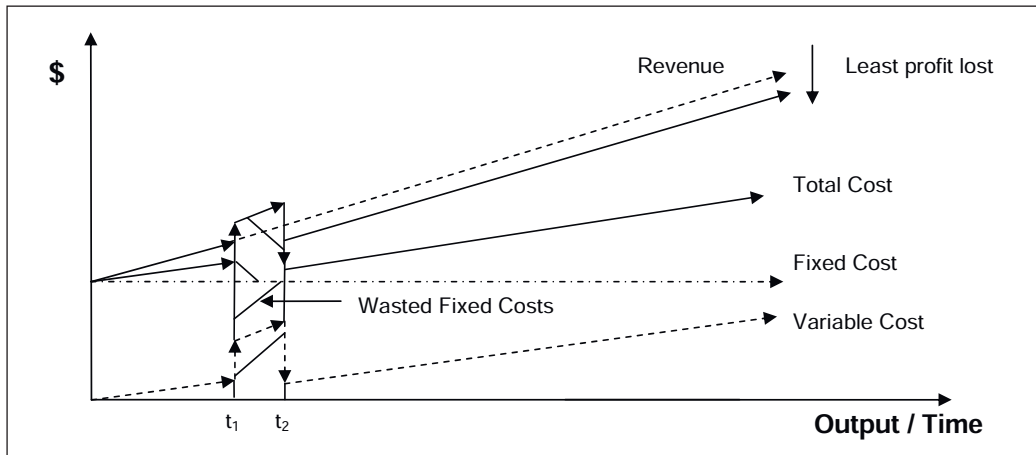


Figure 11.4 – Effects on Profit by Reducing Both Chance and Consequence.

What is interesting with the model in Figure 11.2 is that though costs reduce there will be much frantic activity and ‘fire-fighting’ happening in this operation. Minimising risk by reducing its consequences accepts failure incidents as a normal way of doing business. In organisations that use consequence failure management many things go wrong. Its people wait for the failures and then react to them. In this way the management instil a reactive culture in the organisation. Reducing only the consequences of risk makes work for everyone. This work is all wasted time, money and effort because people and resources spend their time fixing failures instead of improving the business. If you were to walk about in this company you would see that everyone is busy, but little of their time and efforts would add value to the operation; only more cost.

The alternate risk management strategy is to apply chance reduction techniques. In Figure 11.3 there is only one incident during the same period as there were three in Figure 11.1, while all else remains the same. Comparing the two models graphically it is evident that over the same period there is less profit lost with chance-reduction strategies than consequence-reduction strategies. Fewer failure incidents occur because chance reduction stops opportunities developing. Add-up the savings from failure surge costs not spent and you get a very profitable operation. The lower cost strategy is clear: chance reduction delivers less failures because fewer defects are present to rob resources and waste money.

A complete risk management strategy is to use both chance reduction and consequence reduction together to maximise profit. It is far better not to have a failure, but if it does happen you also need to quickly minimise its consequences. Your business processes need to be good at doing both well. The benefit of using combined strategies is evident in Figure 11.4 where both lost time and failure frequency are reduced. The business loses the least profits.

Figure 11.5 lists some of the methods available to address risk. The various methods are classified by the Author into chance reduction and consequence reduction strategies. 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.

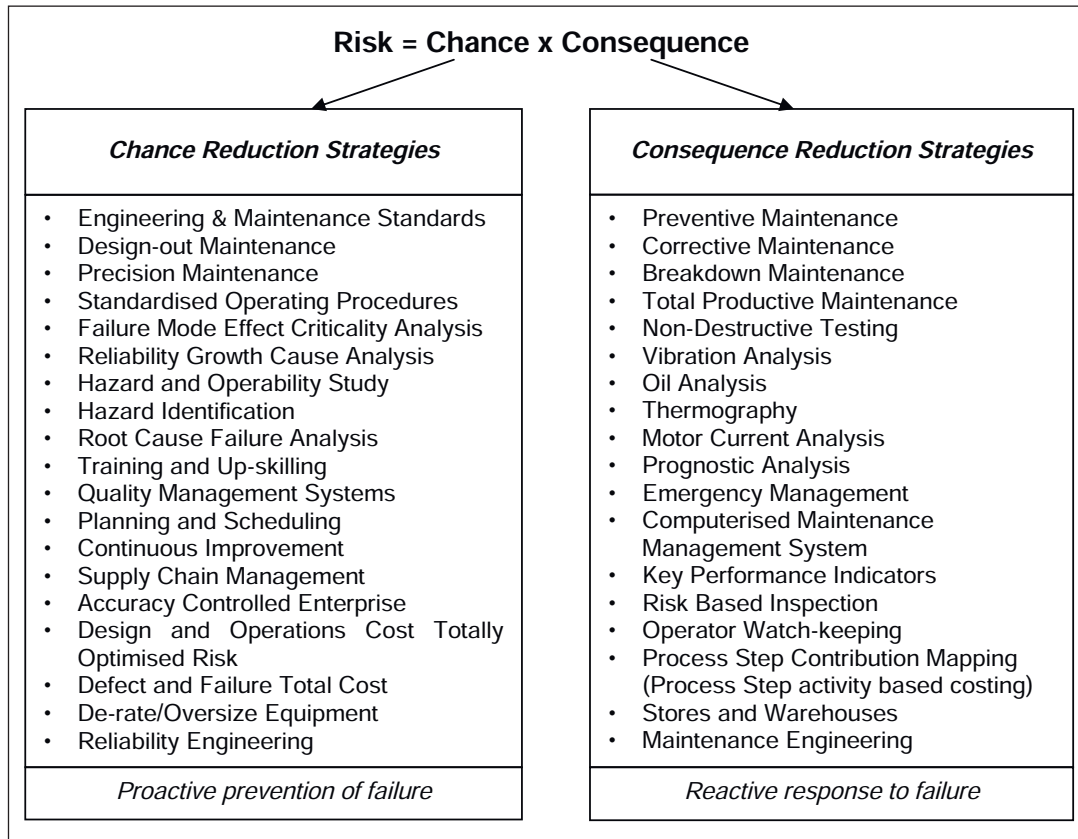


Figure 11.5 – Various Risk Management Processes and Methods.

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 which will remove defects. Those organisations that primarily apply chance reduction strategies truly have set-up their business to ensure decreasing numbers of failures. As a consequence they get high equipment reliability and reap all the wonderful business performance it brings.

### Power Law Implications

Equations of the risk and loss type are special<sup>55</sup>. They are known as power laws and take the general form  $x = z.y^n$ . For the standard risk equation the exponent 'n' is assumed to equal 1. Power laws have particular properties. For example, they are 'scale-free'. In the case of risk it means the risk equation applies to every size of risk. It means that failure costs are not linear, and while one incident may lose a few dollars, another can total immense sums. They are "typically a signature of some process governed by strong interaction between the 'decision-making' agents in the system". This implies that risk does not arise entirely randomly; rather it is affected by the 'decision-makers' present in a system. Situations that follow power laws have a higher number of large events occurring than those of a normal distribution. For risk, this means that catastrophic events will occur more often than by pure chance. In power-law-mirrored events, a few factors have huge impacts while all the numerous rest have little effect. For risk, this means there are a few key factors that influence the likelihood of catastrophe. Control these and you increase the chance of success.

<sup>55</sup> Ball, P., 'Critical Mass – how one thing leads to another', Arrow Books, 2005.

Figure 11.6 shows plots of the risk equation on a normal linear-linear graph<sup>56</sup>. The risk plots as curves. You develop the risk curves by keeping the value of risk constant and then varying the frequency and the consequence through a range of numbers. Anywhere on a curve is the same risk. Figure 11.7 shows the log of the risk equation plotted on a log-log graph. The fact that the logarithm of the risk equation plots as straight lines has special significance. It is an example of how power laws have an uncannily ability to reflect the real world. The insurance industry uses such curves to set insurance premiums because they closely represent what actually happens in human endeavours.

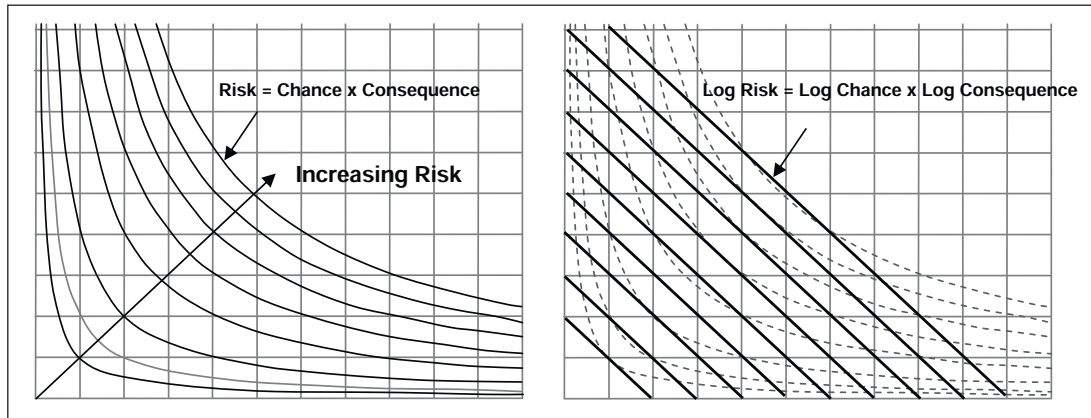


Figure 11.6 – Risk Curves on a Linear Graph.

Figure 11.7 – Risk Lines on a Log-Log Graph.

Power laws that reflect the human world also tell us much about the situations from which they arise. Perhaps the most important understanding from the risk equation being a power law is the presence of ‘decision-making agents’ in a system. Philip Ball in his book, ‘Critical Mass’, points out that, “Physicists’ long experience with power laws ... leads them to believe that such laws are the universal signature of interdependence. A power law generally emerges from collective behaviour between entities through which local interactions can develop into long-range influences of one entity on another.” Our simple risk and loss equations now take on far greater and menacing implications.

Risk reflects the presence of ‘agents’ working uncoordinatedly within a system. The effects of these ‘independent agents’ move through the system in unknown ways. The results of their uncoordinated, and most likely perfectly justifiable, efforts is to increase the risk. We now have another reason why chance reduction strategies are more successful than consequence reduction strategies in reducing long-term organisational risk – chance reduction strategies work on controlling the systems in a business. They align and coordinate masses of people and information, thereby removing the randomness of ‘independent agent’ influence which unwittingly acts to increase the causes of failure and loss. Gradually and continually the chance reduction strategies act to align and organize the efforts of the mysterious ‘independent agents’ playing unscripted parts. The randomness of their actions and effects are reduced, and finally removed. Chance reduction strategies are the total opposite to consequence reduction strategies, which live with risk and failure as normal. Instead, chance reduction strategies forever reduce risk. Because they strike at the random behaviour of the ‘independent agents’ within a company they align people, decisions, actions and behaviours into an over-arching system for achieving organisational outcomes. Chance-reduction strategies remove randomness and unplanned interactions from business systems by specifying an agreed approach.

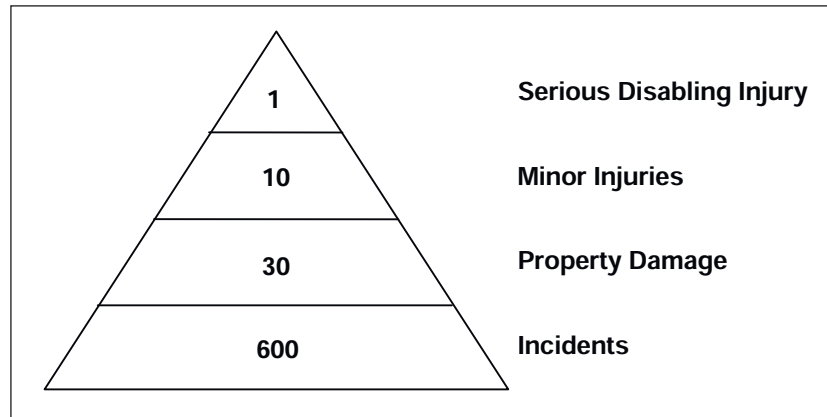
<sup>56</sup> Buckland, Peter, Extract from ‘Boss, we need a new switchboard’ Presentation, Australian Asset Management Council, 2005.

It is in your organisation's best interest, and it will generate the most profit consistently for the least amount of work, to focus strongly on the use of chance reduction strategies. Consequence reduction strategies are still important and necessary – once a failure sequence has initiated you must find it quickly, address it and minimise its effects so you lose the least amount of money. But consequence reduction will not take your organisation to world-class success and profit because it expends resources. Only chance reduction strategies reduce the need for resources because they proactively eliminate failure incidents through defect elimination and failure prevention.

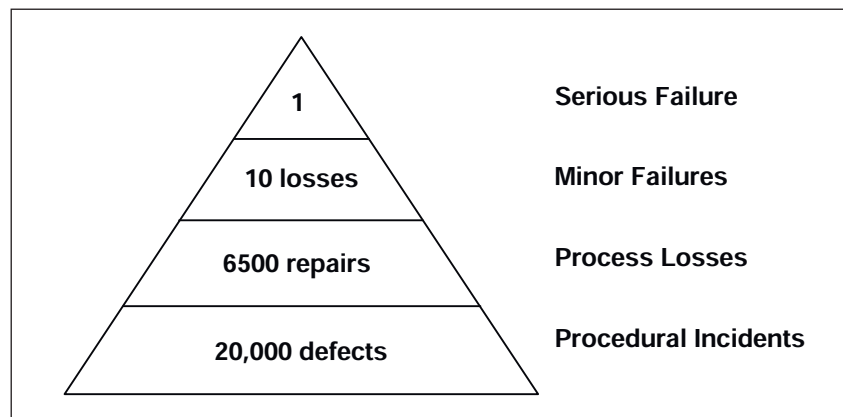
Nothing is certain with risk; it changes with the circumstances. Controlling risk demands that an organisation has the culture and practices to guarantee continuous, rigorous compliance to risk reduction practices, else the chance of failure rises over time as systems degrade. Eventually the worst will happen.

### Similarity between Safety Incidents and Failures

Some consequences of risk will be negligible, and perhaps only an inconvenience at worst, others will be severe, and some catastrophic.



*Figure 11.8 – The Updated Heinrich Accident Pyramid.*



*Figure 11.9 – The Failure Pyramid.*



Figure 11.8 is the updated 1931 H.W. Heinrich accident pyramid that shows for every serious injury there are many minor incidents preceding it <sup>57</sup>. If there are sufficient numbers of incidents, probability means that one will progress to causing serious injury at some stage.

Analysis of historic industrial safety data not available in 1931 highlighted that the safety pyramid is not completely representative of the real workplace. It correctly represents the situation for minor injuries, where reducing the number of safety incidents leads to fewer injuries. But the new data indicated that reducing the number of incidents did not reduce a proportionate number of serious injuries. This is in-line with the realisation that risk is a power law and influenced by the ‘decision-making elements’ within a system. Serious injuries are not accidental but the result of systematic failure caused by unintentional outcomes of uncoordinated ‘decision-makers’ in the system. Current best practice in workplace safety is to actively seek serious injury causing situations before they happen and immediately act to stop them from ever leading to a real injury.

There is equivalent industrial data for the number of equipment failure opportunities needed before there is a serious production breakdown. The concept of a failure pyramid, with many small errors at the bottom leading to ever greater consequence levels above, applies <sup>58</sup>. Figure 11.9 is the failure pyramid for equipment failures.

As with the accident pyramid, the failure pyramid reflects a power law, and stopping minor failures does not prevent catastrophic failures. Catastrophic loss is not controllable until the ‘decision making elements’ in a system are controlled. Like minor safety injuries, minor equipment failures can be reduced by preventing the numerous and ever-occurring small errors that precede them. But to address catastrophic failures you must intentionally imagine the worst outcomes, then proactively put into place the necessary measures to prevent them from ever happening. The Plant Wellness Equipment Criticality process adopts that logic. The DAFT Cost can be immediately calculated for the full consequential costs of an event. Should the consequential costs be too high, additional protection measures are immediately included to lower the chance of occurrence. Frequency is an unimportant consideration in failure prevention because when catastrophe happens is unknowable. We must always be prepared. By first identifying the full cost of failure, our risk adverse natures prompt us to take wise precautions when the cost of being wrong is too extreme.

Even if the frequency of occurrence could be determined, the nature of risk, with its independent actors all playing unscripted parts, means the frequency will not stay the same. This implies that basing risky decisions on things not changing for long periods of time is fraught with danger. It is highly unlikely that frequency remains constant, because factors totally unknown and unknowable caused by the ‘decision-making agents’ are forever altering the future. What worked for us one day to prevent failure may not work the next day because failure has found a different route. Our only protection against risk is to be ever vigilant of its presence – look for its warnings, foresee and eliminate those that we can, and prepare yourself to fight back when it finds new ways to attack.

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### **Example E11.1 – The Titanic Disaster – When Gaps in Protection Systems Align**

There is one further concept about risk that is worth understanding, and adds to the justification of managing risk by chance reduction rather than consequence reduction. Catastrophic events, where life is lost and great costs result, do not often happen. For catastrophic loss to happen it requires the sequential failure of a number of overlapping protective systems.

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<sup>57</sup> Saldaña, Miguel A M et al., ‘Assessing Definitions and Concepts Within the Safety Profession’, International Electronic Journal of Health Education, 2003; 6:1-9.

<sup>58</sup> Ledet, Winston, The Manufacturing Game, Ledet Enterprises Inc., 2002.

The iceberg was not the only reason the Titanic sank and caused great loss of life. The captain ran the ship at high speed during fog conditions in iceberg prone seas. The rudder was too small. The ship was not fitted with sufficient safety boats for its entire complement of passengers and crew. The ship designers incorrectly deemed it as unsinkable through gross misunderstanding of the capability of the engineering design. The steel specified for use to build the vessel was crack-propagation prone.

On the night of the fateful disaster all these failures, errors and mistaken decisions aligned when the ship hit the iceberg and a great loss of life resulted. Like rubbing two palms together with outstretched fingers, when the fingers align a gap appears. So it was with the Titanic, the gaps in each layer of protection – operating procedures, safety practices, design assumptions, material selection – appeared and nothing was left to prevent a catastrophe.

The many small failures that happen in a business, such as misread numbers, incomplete information, wrong material selection, training not provided, poor procedures and documents, short-cutting tasks, and many other similar blunders, will at some future time allow the gaps in protection to align and cause unwanted problems to pour through and drown the business and its people.

Prevent failure incidents by providing numerous layers of various protections, and do properly the requirements for each layer. As with improving reliability, the more independent parallel proof-tests used for each activity, the fewer errors get through to later cause problems. Perhaps a minimum is to have three independent, unconnected layers of protection in place everywhere. For example, in a production environment start with well-documented, accuracy-controlled procedures, then add thorough training and retraining and finally a comprehensive testing and audit process of workplace practices. A second example is a capital project to increase plant capacity. Start the design with detailed and clear operational, equipment reliability and financial performance requirements written by the 'customer'. During the design phase, test and prove the proposals will deliver all requirements by prototyping, modelling or third-party review. The third layer is to conduct thorough and comprehensive reliability, availability, maintainability, safety and profitability studies and reviews with the 'customers' involvement prior to purchasing plant and equipment.

Before deciding the number of protective layers you need for a situation conduct a risk analysis and let the results of the analysis determine the final number of protective layers required to deliver the risk control certainty needed. Organisations that do not have multiple ways to prevent failure or problems, or do not demand and enforce the proper and full adherence of installed risk management practices, will always suffer losses, high costs and much waste – how can it be otherwise when they have not protected themselves properly.

## Selecting Maintenance Strategy for Risk Management

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 Figure 12.1 shows the process used in the Plant and Equipment Wellness Methodology to match maintenance strategy for an equipment asset to its business-wide risks.

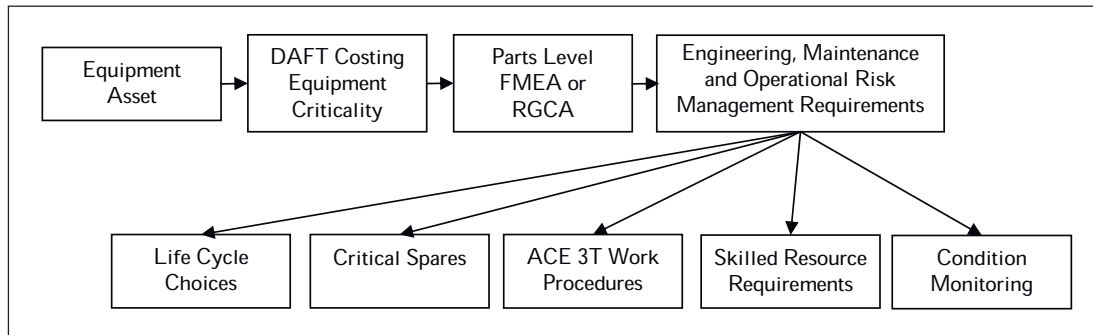


Figure 12.1 – Developing Maintenance Strategy for Risk Management.

Table 12.1 overlays engineering, maintenance and operations risk management activities onto a risk matrix to show how methodologies and activities can be selected and matched to business risk in order to protect a business from potential failures and catastrophe.

Table 12.1 – Maintenance Management Strategies Matched to Risk Levels.

Consequence		Insignificant	Minor	Moderate	Major	Catastrophic
Frequency		1	2	3	4	5
6	Certain	PM / Precision	CM / Precision	Precision / Design-out	Design-out	Design-out
5	Likely	PM / Precision	CM / Precision	Precision / Design-out	Precision / Design-out	Design-out
4	Possible	PM / Precision	PM / Precision	CM / Precision	Precision / Design-out	Precision / Design-out
3	Unlikely	BD	PM / Precision	CM / Precision	CM / Precision	Precision / Design-out
2	Rare	BD	PM / Precision	PM / Precision	CM / Precision	CM / Precision
1	Very Rare	BD	PM / Precision	PM / Precision	CM / Precision	CM / Precision

## Equipment Criticality Assessment

The aim of assessing equipment criticality is to identify the severity of the business-wide impacts if an equipment asset fails. The process develops clear, justifiable strategies to reduce risk by applying the methods explained in Chapter 8 – Operating Equipment Risk Assessment.

### **Failure Mode and Effects Analysis or Reliability Growth Cause Analysis**

Failure Mode Effects Analysis investigates the ways that the parts in a machine can fail when in use and identifies the actions to be taken to prevent the failure. The methodology uses a cross-functional team of experienced people to remove the various modes of failure for each part. They develop the corresponding plans and actions to prevent the failure and/or minimise the consequences. It can be applied to civil, structural, mechanical, electrical, communications or instrumentation assets, and the like.

Reliability Growth Cause Analysis considers all life-cycle risks an equipment part will face that can cause it to fail. Like FMEA, a competent, cross-functional team is needed for the analysis, but the focus is vastly different. An RGCA looks for ways to make equipment parts live outstandingly long lives. How to apply a Reliability Growth Cause Analysis is explained in Chapter 18 – Reliability Growth.

### **Plant Planned Maintenance and Operating Strategy**

It is now time to summarise the contents of the book into a methodology for identifying the maintenance and operational strategies and activities that create plant and equipment wellness. The development of a strategy starts by stating the outcomes required. They may not be easily achievable, but you only have to continually improve your processes and they will be realised.

#### **Set the Objective**

Set measurable objectives based on the asset management and maintenance policies. For example:

- a. To reduce the maintenance costs in the plant to 2.5% of replacement asset value.
- b. To reduce breakdown maintenance costs below 10% of total maintenance cost for the plant by instigating defect elimination practices and conducting planned maintenance activities that renew plant and equipment before failures occur.

#### **Methodology to Follow**

The method to achieve the above objectives are summarised in the following steps;

1. First check what proportion of current maintenance effort is reactive work fixing things, versus pro-active work that stops them from failing in the first place. You want to be spending most of the maintenance time doing proactive work (defect elimination). Also identify what proportion of the maintenance effort is actually assisting project or production groups and not doing maintenance related work.

Review the last two years of maintenance work history and separate into four categories of Proactive, Reactive, Improvement and Assistance work. Compile costs and man-hours per category to determine proportions of cost and effort spent for each. The Proactive category includes preventive maintenance, predictive condition monitoring, design-out maintenance, statutory maintenance, etc. Reactive includes corrective repairs, breakdown maintenance, emergency maintenance, safety or incident related maintenance, etc. Improvement includes equipment or process modifications to improve reliability. Assistance is maintenance resources used for capital projects, plant upgrades, production requests, etc.

2. Draw the process maps for each production line and for each equipment item in the line. Collate the equipment list from plant drawings, instrument and process diagrams and equipment asset lists. Be sure to capture all equipment in operation, as it will later be necessary to go to assembly and component levels of analysis. Ensure every equipment item required to run production is on a process map. This includes items used only at start-up or shutdown.
3. Logically divide the production process into definable sections. Put the full list of production line equipment used in each section of the process into the Risk Identification and Grading spreadsheet on the CD accompanying this book. For each section, list each item of equipment in the order encountered in the process, along with its assemblies and parts. List down to the lowest identified part number in the Bills of Material.
4. Determine the business-wide DAFT Costs for each equipment item. The DAFT Cost for equipment or assembly parts failures is used to make decisions on whether or not it is worth doing risk mitigation activities. Repeat this for all assemblies and components in the respective equipment. For each item of equipment, record what assemblies and parts are critical for the equipment to operate correctly and produce quality production. As a consequence risk reduction strategy, it may be necessary to keep some of these parts as spares if their failure jeopardises the business.

For a parallel activity to check the DAFT Cost impacts, rate the most severe impact of individual equipment failure on a 5-point scale. 1 is immediate and total impact; major injury requiring hospitalisation or worst; permanent environmental damage. 2 is delayed total impact; medically treated injury; rehabilitatable environmental impact. 3 is reduced or hindered operation. 4 is inconvenience to operation. 5 is no impact. You have now determined the severity to the business for all its equipment and identified which assemblies and components are critical to its operational success.

5. From CMMS records and operating records identify failure frequency and annual maintenance costs per equipment. You need a representative period of time that reflects the effects of an operation's culture and management practices. Five or more years is ideal. If the plant was upgraded, or the process changed, then take the records from the date of commissioning the change. Where job costs are reliable and accurate, identify costs, man-hour and materials required for regularly recurring work to assist future estimating and planning purposes.
6. Using Pareto analysis, identify the high maintenance cost equipment recorded in the CMMS. Each of the top 20% most costly equipment can also be analysed using double-Pareto to identify their failure causes and pinpoint possible solutions.
7. For a double check, and as a parallel-test activity on work done so far, conduct an on-site tour and review of plant and equipment with experienced Operations and Maintenance personnel to identify operating problems not reflected in the maintenance records. Identify problem equipment, failure frequency, consequences and critical parts required for each plant asset. Confirm you recorded all issues from the site tour and the CMMS review in the Risk Identification and Grading spreadsheet.
8. Perform a Plant Wellness Equipment Criticality analysis.
9. In priority order of equipment criticality, conduct a parts hardware-level FMEA, or RGCA, with experienced engineers, operators and maintainers. Identify at-risk parts and select activities to address the risks. Mitigations can be chance and consequence reduction strategies payable by the DAFT Cost savings they deliver. In preference use chance reduction strategy ahead of consequence reduction.

Using the Risk Management Plans spreadsheet, create planned maintenance activities to

perform preventative maintenance, condition monitoring, renewal or refurbishment of equipment and components. Set the timing and the quality standards of each activity so that the activity prevents the failure. The quality standards to adopt are those world-class best practice requirements that significantly reduce stress in the parts.

Secondly, with the help of operations personnel develop operator inspection and check sheets so that operators can perform watch-keeping activities during their normal rounds.

Third, review if the current planned and preventative maintenance activities are still relevant, or need to change to suit the new planned maintenance requirements.

Fourthly, include maintenance activities for statutory compliance, quality control, safety hazard mitigations, and the like, not identified by the FMEA/RGCA.

10. Confirm planned activities significantly reduce risk by a minimum of two levels on the risk matrix for Extreme and High rating, and to low for Medium ratings. Ensure significant reductions in the Physics of Failure and parts environmental stress factors.
11. For each item of production equipment, financially model the new planned maintenance activities and compare the new cost to the current maintenance costs to provide economic justification for changing maintenance and operating strategies. Review the new balance of costs between expected Reactive and Proactive categories to confirm the majority of time is on proactive pursuits.
12. With help from maintenance planners, develop each planned maintenance activity into ACE 3T 'good, better, best' banded procedures. To help future job planning, include a scope of works with itemised tasks, materials list and cost estimation. Provide materials lead time indication, trade man-hours estimation and the total work order cost estimate.
13. Catalogue and cost the spares identified as critical requirements for plant and equipment from the FMEA/RGCA.  
  
Detail the spares required for planned maintenance activities each financial year for inclusion in the annual financial budget.  
  
Update critical spares list and order spares in a controlled and financial responsible manner.
14. Prepare the maintenance schedule and budget in advance for the next two years, including factoring the improvement effects on equipment reliability of the new planned work orders. Update the CMMS with the new planned work order details. Develop the resulting maintenance resource demand into an overall resource schedule.
15. Submit the plant maintenance budget into the corporate accounts
16. Track each production plant's equipment reliability performance to ensure it is improving.

### **Flow Chart of Planned Maintenance Strategy Process**

Figure 12.2 is a summary flow chart of the methodology. Bullet-point comments on the requirements and aims of selective steps follow.

#### **Collect Historical Information**

- Gather Process Flow Diagrams, Process and Instrumentation Diagrams, Equipment Asset List
- List all equipment units and interconnecting processes in a spreadsheet.
- Insure all equipment has an asset number (tag number).
- Create a full and complete list of plant equipment assets.

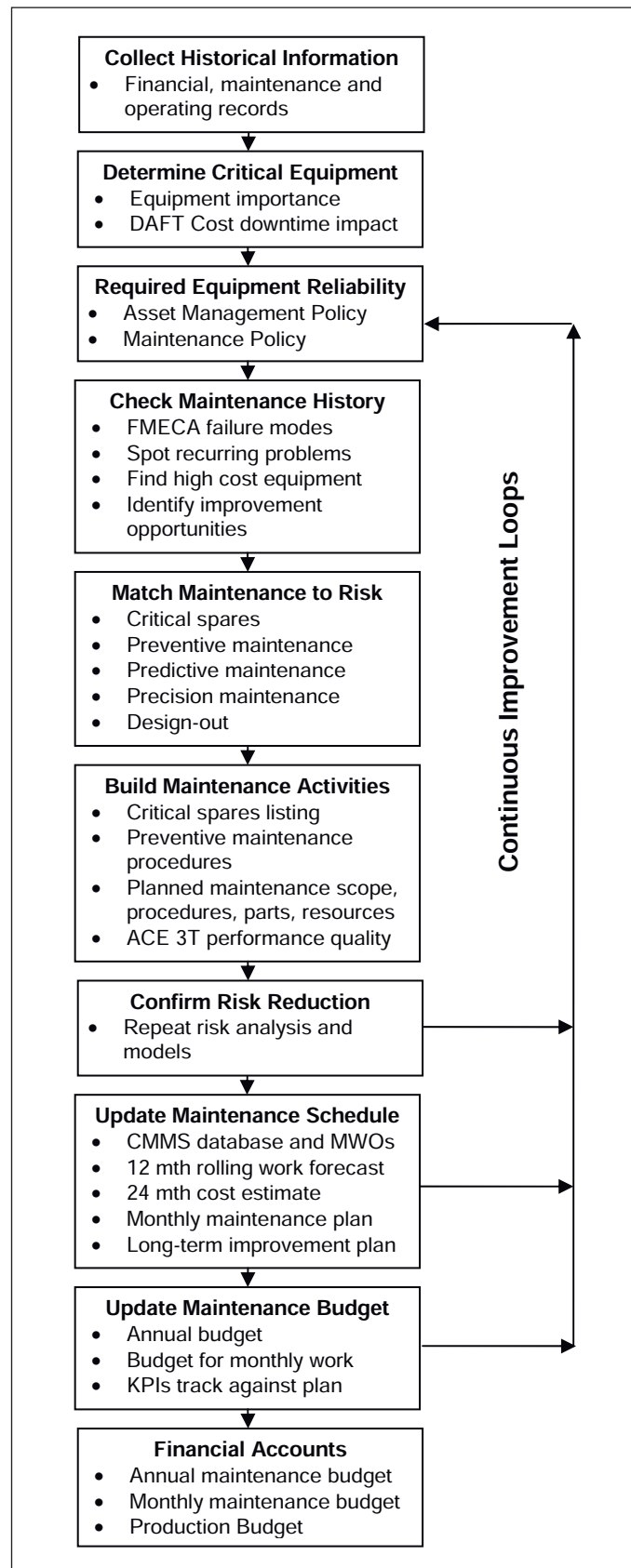


Figure 12.2 – Planned Maintenance Flow Chart.



- Group equipment assets into their process function, e.g. Bulk material handling, mixing, reaction, storage, filtration, filling, etc
- Draw the process maps

### **Criticality Assessment**

- List all plant used for a process function into a spreadsheet. For individual plant, list each piece of equipment and its primary assemblies. Under each assembly, list components. Continue listing working components until all working items on the bill of materials for each assembly are recorded.
- From equipment maintenance history, identify the annualised number of failures for equipment, assemblies, sub-components, and parts.
- Taking a piece of equipment/assembly one at a time, use DAFT Cost of Failure to rate the worst impact of its failure on the business. Use the consequential cost to get a risk matrix rating for the item (E, H, M, L) and a risk number (add together the numeric values for 'likelihood' and 'consequence')
- Reduce the DAFT Cost and risk number value by deciding what operating activities and maintenance types an item requires to ensure stresses are significantly reduced to produce a long, low-stress service life.

### **Review, Categorise and Proportion Current Maintenance Efforts and Costs**

- Differentiate all historical work orders into primary categories identifying the reason for the work order. Typical examples at 'Failure' related, 'Preventative' related, 'Improvement' related, 'Assistance' to Production related.
- Determine the total material costs, labour costs and labour hours for the period expended by in-house maintenance trade type and by contracted services/trade type in each primary category.
- Determine the proportion of hours and costs in each primary category to identify which are disproportionate to the risk reduction value they provide.

### **Identify High Maintenance Cost Equipment from CMMS**

- Analyse past work orders and history to identify problem equipment with high costs, repetitive failures, and long downtime.
- Collect repair times and costs for work on high maintenance equipment to use in estimating future planned maintenance jobs.
- Identify those items of plant that require engineering review to design-out problems. An engineer or the like will need to address these.

### **Pareto Analysis of High Cost Equipment**

- Review work order costs for last two financial years and categorise equipment in order of cost to the business.
- Review numbers of work orders against each item of equipment for the last two financial years to determine which equipment are a high drain on maintenance resources.

### **Plant Review with Operators and Maintenance Technicians**

- Taking each equipment item one at a time, find out from an experienced operators and experienced mechanical and electrical maintainers, what goes wrong with the equipment and how often. Record any comments on necessary spares, causes and solutions to the failures.
- Compare back to the CMMS history review to confirm the degree of the problem. What operators and maintainers perceived may not be noted in the CMMS records.

### **Conduct an FMECA/FMEA or RGCA**

- Gather a cross-functional team and do a parts-hardware level FMEA, or perform the life-cycle encompassing Reliability Growth Cause Analysis to identify the means for preventing parts failures.

### **Create Planned Maintenance Activities to Address Equipment Failure Frequencies**

- Based on severity and frequency of failures develop planned operating and maintenance activities to reduce future occurrences. Select the activities and set quality standards that will stop parts failure from operational stresses.

Include requirements for statutory compliance of equipment. Use ‘roundtable’ meetings of maintenance trades, operations personnel and experienced engineers to get consensus.

- Develop for each identified item of equipment a list of Preventive Maintenance (PM) parts replacement and Predictive Maintenance (PdM) condition monitoring tasks to be performed.
- Record estimates of trades, times, additional resources and materials to do each PM and PdM.
- If operators can do the maintenance activity well, identify it for discussion with the operations manager as the start of a Total Productive Maintenance (TPM) program.

### **Detail the Critical Spares Required**

- Based in the criticality analysis, CMMS review and FMEA, compile the critical spares required, listing the model details, part number and supplier.

### **Develop Planned Maintenance Activities**

- In order of equipment criticality, develop the specified planned activities.
- Include a full work scope, materials list, materials cost estimate, lead time for materials, trades requirement, trades time estimate, labour cost, ancillary items and costs.
- Produce ACE 3T precision procedures for all activities.

### **Confirm Risk Reductions**

- The effect of activities to reduce parts’ risk are assessed to ensure that they do deliver the needed risk reduction. Use the Risk Treatment Schedule and Action Plan Template, Table 8.5, to gauge that the total effect of proposed actions will reduce current risk level sufficiently. Alternately, a spreadsheet such as that for Risk Reduction in Table 8.6 can be extended to include the action plans and the confirmation that they will significantly reduce risk.

### **Model Revised Costs Based On Likely Results of New Maintenance**

- Do a spreadsheet analysis to estimate the cost of using the proposed planned maintenance and frequency of tasks. Compare it against current costs and proportions of work effort.

### **Prepare a Planned Maintenance Schedule and Budget for the Coming Financial Year**

- For each production plant develop a forecast maintenance budget based on the new planned activities. Include all statutory compliance requirements, any planned equipment replacements, along with any site specific work that is done on the maintenance budget.

### **Submit Revised Maintenance Budget to Corporate and Track Performance**

- Role the new forecast maintenance costs for the plant into the company wide budget.
- Trend and monitor each plant's monthly breakdown performance with suitable Shewhart control charts using 3 sigma limits and/or with appropriate KPIs.
- Investigate special cause discrepancies and rectify them as appropriate.

### **Example of an Equipment Risk Reduction Strategy**

Developing a maintenance strategy to prevent failure of a centrifugal pump-set would start by drawing the process map for the equipment. The pump-set could fail for many reasons, as could any of its parts. The wet end could fail, the shaft bearings, the shaft coupling, the motor internal parts, the power supply to the motor, and the mounting frame or foundation plinth may fail. Each of these assemblies must be analysed in detail to spot the risks they cause.

From the analysis a maintenance strategy that delivers high reliability for each assembly is developed. An example of an operational and maintenance risk reduction strategy for the pump bearings is shown in Table 12.2.

If the proposed operational and maintenance strategy in Table 12.2 is carried out properly it will ensure the pump bearings have a long, failure-free life. The precision maintenance laser alignment removes the chance of overstressing parts and the inspections remove the risk of unknown environmental and operational degradation. The likelihood of a bearing failure event on the risk matrix has gone from 'likely' to 'very rare' and the criticality from High to Low.

The development of the risk control strategy then continues for each piece of equipment, assembly by assembly, failure mode by failure mode. There is great effort and time required in doing this level of risk assessment and risk control. It is the only way to ensure that risk is understood thoroughly enough to protect the business by greatly reducing the chance of catastrophe for the operating lifetime of the equipment.

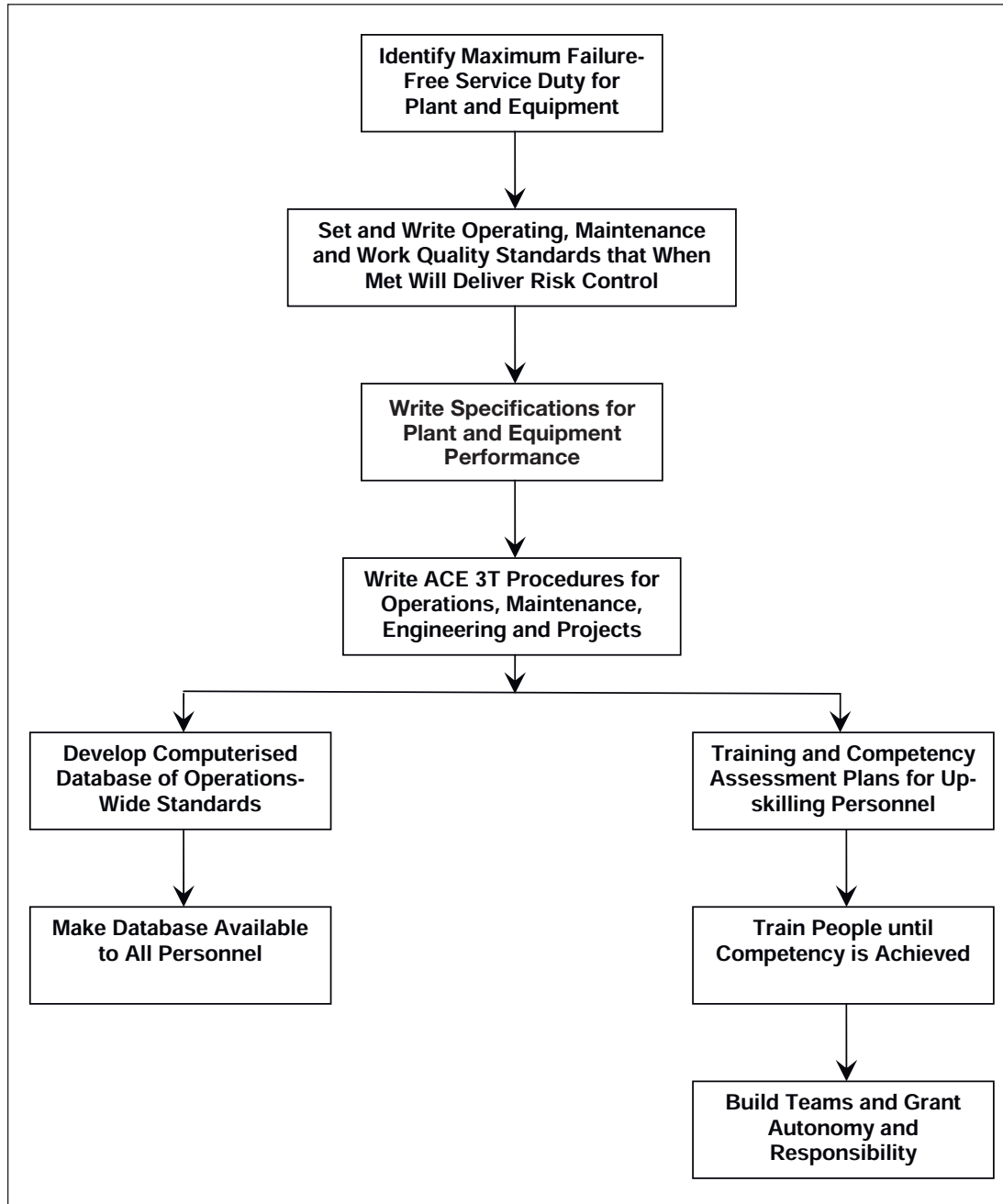
The Operating Risk Control Methodology only produces understanding and pieces of paper. What is now vital is to actually do the risk reducing activities. The Accuracy Controlled Enterprise methodology is used to ensure the correct work is done so well that the chance of a failure is greatly reduced.

Table 12.2 – Example Pump Bearings Reliability Strategy Development.

Equip Tag No	Current Failure Events	Failure Events Frequency	DAFT Cost of Failure	Risk Reduction Activity	Improvement Expected	Freq of Activity	Cost / Yr	Failure Event Reduction
Pump 1	Bearings fail	2 years	\$35,000	Laser shaft alignment to precision practices every time the pump is installed	A precision alignment is expected to deliver 5 years between bearing failures	Every strip-down	\$200	Failure interval now likely to be greater than 5 years
				Oil and wear particle analysis every 1,000 hours of operation	Oil and Wear Particle Analysis can indicate the start of failure several hundred hours prior the event	1,000 hrs or Six monthly	\$600	Failure will be prevented by a predictive planned condition monitoring task
				Visual inspection by the Operator each shift of the oil level in the sight glass	Visual inspection of the oil level ensure the bearings are always lubricated	Every Dayshift	No cost	Failure will be prevented by operator condition monitoring
				Operator physically touches pump bearing housing each week to feel for changed temperature and vibration	Touching the bearing housing will identify impending problems before they cause failure	Wednesday Dayshift	No cost	Failure will be prevented by operator condition monitoring
				Motor load monitoring using process control system to count overloads	Monitoring the electrical load will identify how badly and how often the equipment is stressed by overload	Continuous with monthly report to Ops Manager	\$100	Poor operating practices will be identified and personnel trained in correct methods
				Pump performance monitoring of discharge flow and pressure using process control system	Monitoring the pump performance will indicate gradual changes of pump internal clearances affecting service duty	Continuous with monthly report to Ops Manager	\$100	No direct impact on reducing risk of pump failure, but identifies performance drop and allows planned maintenance to rectify internal wear.



## PROCESS 4 – Introducing Risk Control



## **Description of Process 4 – Introducing Risk Control**

### **Identify Maximum Failure-Free Service:**

Indicate in the FMECA Spreadsheet how long the equipment is required to run without unplanned downtime, safety issues, production slowdown, or product quality problems. This allows measurement of the effectiveness of the risk control strategies and provides means to prioritise improvement efforts.

### **Set and Write Operating, Maintenance and Work Quality Standards:**

Set performance standards that deliver the operation specified. Meeting the standards will produce the operating performance needed from an item of equipment. What workplace cleanliness standard will the operators need to meet to reduce shaft seal failures? What lubrication cleanliness will give the failure-free life required from bearings? What materials are to be used for a particular service life? If world-class performance is wanted, you must set and meet world-class standards.

### **Write Specifications for Plant and Equipment Performance:**

Script the future. The performance standards need to become equipment and process specifications. They indicate what function each item of equipment is to deliver and how to achieve that performance. There must be specific targets with measures to prove the performance meets the standard.

### **Write Accuracy Controlled Enterprise 3T Procedures:**

Every activity and job requires high-reliability procedures. Each task quality is made clear to the person responsible so they know the excellence and accuracy they need to deliver.

### **Develop Computerised Database for all to Use:**

The best practice standards, specifications and procedures are in a database that everyone can access. People have the information to run the operation in the best way to ensure least operating risk. These are valuable and important documents that people need to use all the time.

Visual indicators of performance are displayed so everyone knows his or her workplace performance and that of their team.

### **Training and Competency Assessment Plans:**

With performance standards and 3T procedures set, develop training plans to lift managers, engineers, supervisors and workers competency to meet the required performance.

### **Build Autonomous Cross-Functional Teams:**

Establish cross-functional teams of people responsible to run a process. Keep teams smaller than 100 people so comradeship develops. Subdivide large processes into smaller ones if



necessary. Whether making a product or providing a service, use series and parallel reliability principles to build teams with the skills and knowledge to competently do the required work. Remove all direct management supervision of the team and instead provide necessary training to team members to develop the knowledge and skills to work as a team. You want to create a community with positive spirit. Let the team profit-share in the additional operating profits they generate above the historical maximum from the process.

### 13. Organisation Structure and Teams (A Reliability Based Model)

To get high equipment reliability it is necessary to set-up an organisational structure that can deliver it. Reliability reflects the design choices, operating methods and maintenance practices used throughout the life-cycle of equipment. High reliability needs relevant knowledge and skills at each phase of the life-cycle. For example, if the production group run and manage equipment alone they do not usually have the full understanding needed to run it most reliably and profitably. Due to ignorance and mistaken beliefs they cause unnecessary failures and waste. Operations need the support of cross-functional experts with finance, engineering and maintenance knowledge to get their best performance. Figure 13.1 shows the Author's observations during his career of the effect of organisational structures and departmental focus on plant availability.

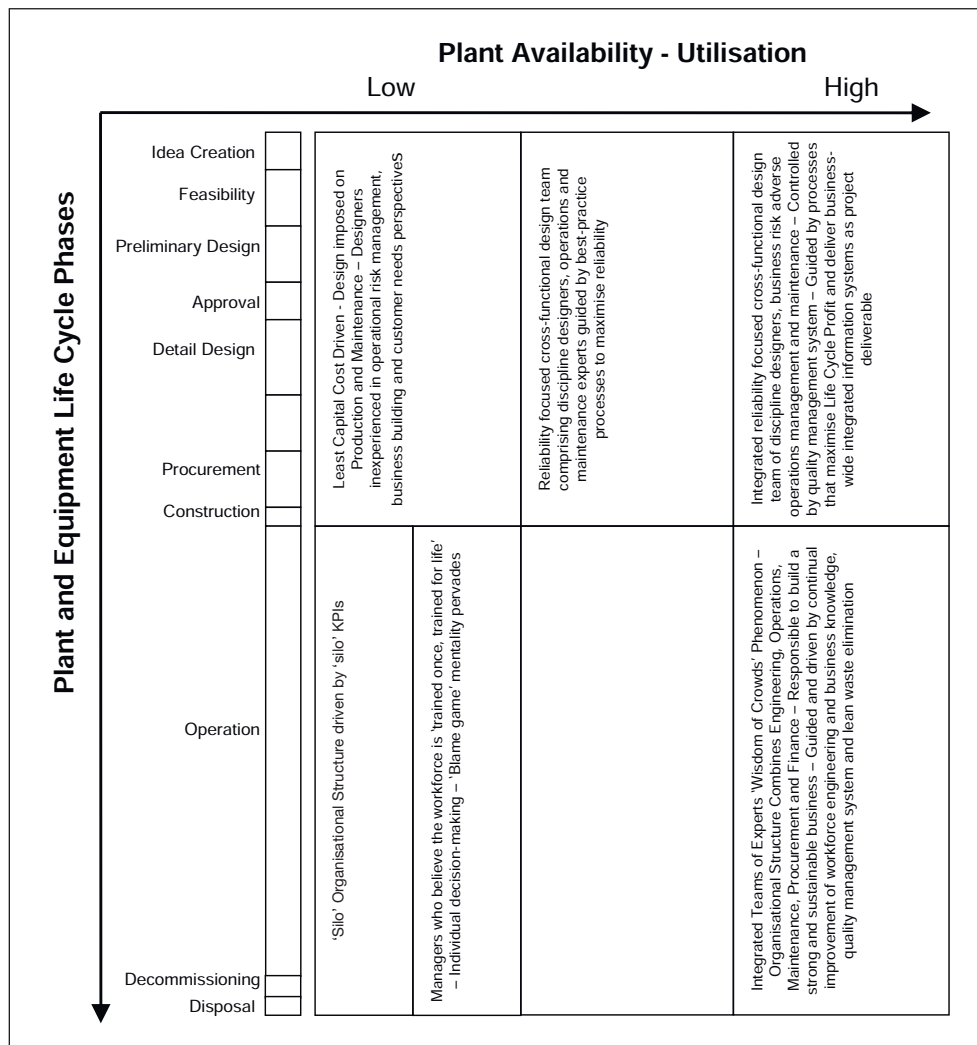


Figure 13.1 – Effects of Organisational Processes and Structure on Plant Availability.

A person working alone and making decisions themselves is at serious risk of causing failure. They are decision-making alone in a series process. One error of judgement in one step of the process will fail the entire outcome. Perhaps not immediately, but eventually. Working alone in any series process is a high risk activity. To protect people making decisions put them into a parallel arrangement where they must get more information and be better informed on their choices. Figure 13.2 shows a decision requiring several parallel activities in order to reduce the risk of conclusion error.

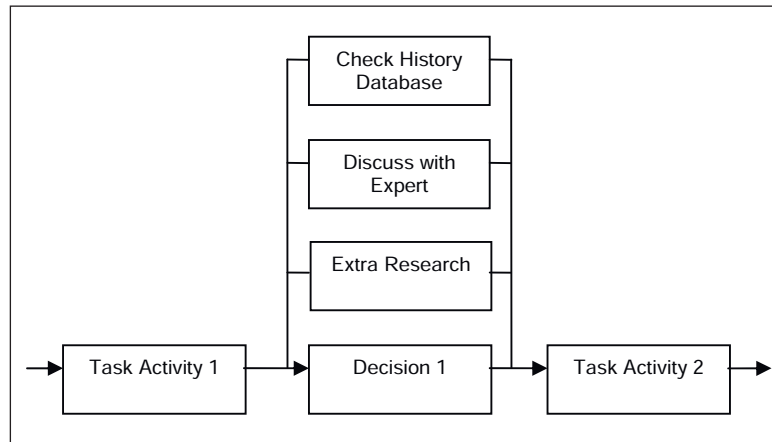


Figure 13.2 – Increase Reliability of Decisions by Making Them a Parallel Activity.

Equipment reliability increases when opportunity is provided for use of more skills and knowledge in the selection, operation and care of the equipment. Setting-up autonomous work teams of people with the right skills and knowledge to increase reliability is a Series System Reliability Property 3 activity. The change to using skilled, cross-functional teams will magnify the reliability of the whole operation because teams combine members knowledge and skills to make better decisions.

### The Reliability Improvement Value of Autonomous Teams

Figure 13.3 is a simple process map of a pump delivering water to equipment. To get maximum reliability from the pumping system the mechanical engineering of the equipment has to be correct, the selection correctly done, and the equipment installed correctly, operated correctly and maintained correctly. Similarly, the electrical and control engineering need to be designed correctly, then selected, installed, operated and maintained correctly. A competent operator would typically only know how to do one of those ten activities – operate it correctly. Some operators may dabble in the pump's mechanical maintenance, but few would be experts.

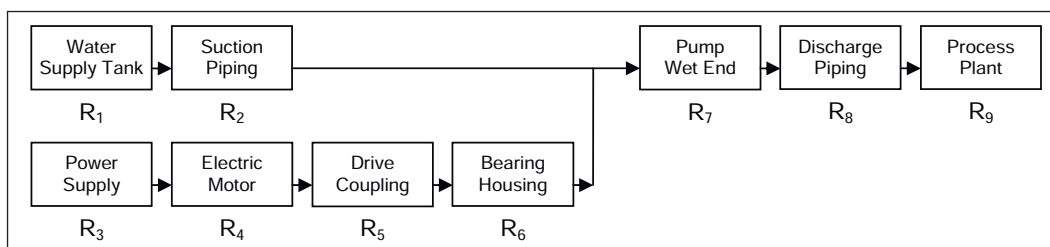
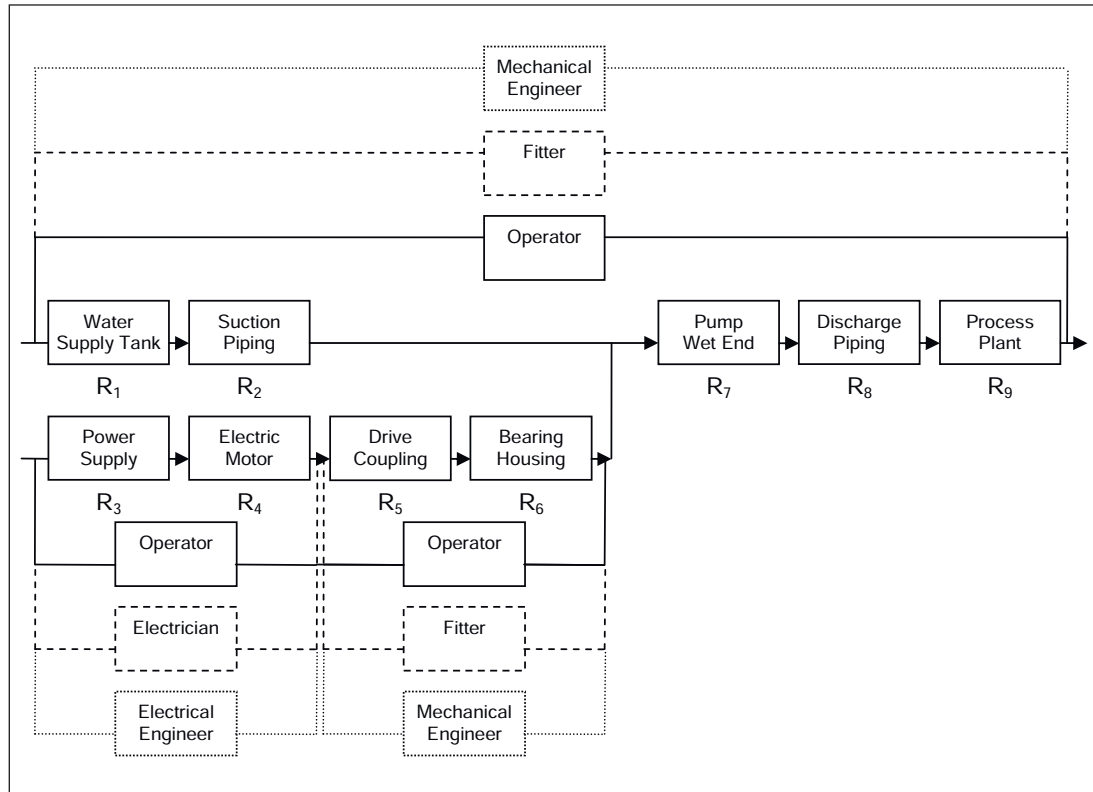


Figure 13.3 – Water Delivery Process Map.

No one is an expert in everything that must be done to have exceptional equipment reliability – there is far too much for one person to know and do expertly themselves. But in a team where each member is proficient in an area of expertise their skills and know-how become available to all the team.

The benefits of a team approach to running business activities become clear when it is realised a team is a parallel arrangement. Figure 13.4 shows the parallel arrangement that teaming-up produces for our pumping system. A mechanical fitter and an electrician are teamed into the operations group. They bring their specialist equipment knowledge and trade skills to the team. Professionally qualified engineers are appointed to work in the team. The engineers bring their

added technical knowledge and understanding to the team. The team gains the engineering skills, experience and information needed to achieve high reliability. Each team member learns to call on the situational expert for advice and information before making decisions. This does not mean that people move to new jobs; rather they fill a team function and become team members who work together and develop a team approach in running and caring for plant and equipment. Some people will be in many teams.



*Figure 13.4 – Teams Parallel Skills and Knowledge to Produce Reliability Improvement.*

### Using Reliability Principles to Create Organisational Structures

There is something very powerful about working in teams. That power comes from the team structure and dynamics. Managers who want higher reliability, top quality production and fewer problems need to understand why teams are so powerful and how to gain that power for themselves.

Reliability concepts can be used to design organisational and business department structures. Teams increase reliability because they parallel the knowledge and skills of its members to produce better performance from plant and equipment. Paralleling people for greater reliability stems from the following two parallel process reliability principles.

1. The more components in parallel, the higher the system reliability.
2. Reliability of a parallel arrangement is higher than that of the most reliable component.

An organisation brings people together to produce an output wanted by its customers and stakeholders. The organisational structure connects people together in their efforts. The quality

of the output is dependent on the peoples' skills and the business processes.

The hierarchy structure shown in Figure 13.5 is typical for most organisations. It is an organisation structure that developed from fighting battles and wars. It is a poor structure for helping companies to achieve their goals because it requires managers to make decisions alone, often hurriedly. It is a high risk design for long-term business success. It encourages managers' egos and ambitions to drive their decisions, rather than making decisions based on careful analysis and understanding of a situation. It promotes human conflict because the person at the top has final authority, yet that person maybe incompetent, ignorant or ill. In those organisations that want top quality products, high equipment reliability and world-class production, such a structure is unsuited to the purpose.

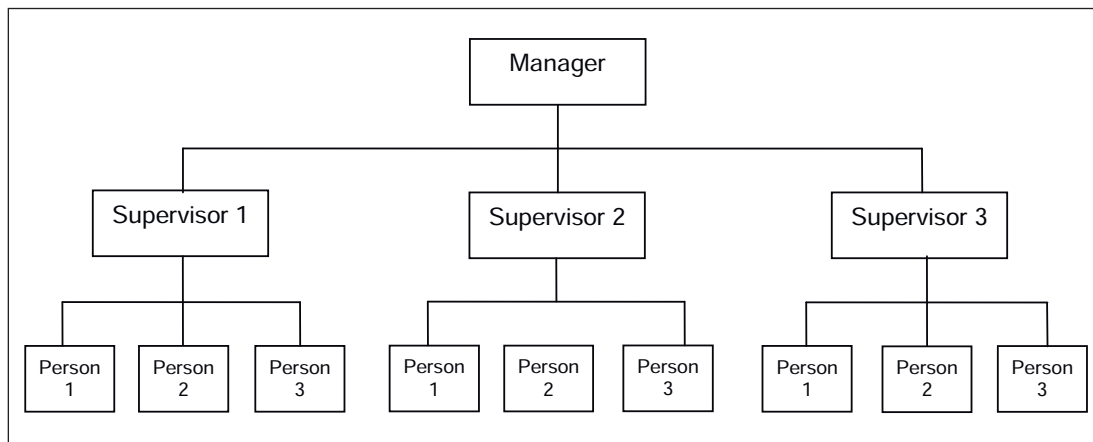


Figure 13.5 – Teams Parallel Skills and Knowledge to Produce Reliability Improvement.

There is a scientific reason why teams improve the chance of success. A team-based decision-cell structure is mathematical a better design for a business than the militaristic hierarchy structure used in most organisations. Group decisions are more likely to be better choices if the conditions are established to promote mutually beneficial interaction<sup>59</sup>. Reliability maths offers deep insights into why and how teams can get better outcomes, and especially why they are a powerful structure for achieving business goals.

To understand the science of how teams and teamwork provide improved quality, reliability and risk control, it is necessary to understand first how work gets done. In Chapter One we identified that all work is a series of actions done one after the other. The sequence of actions makes up tasks. The accumulated tasks make up jobs. This forms a series process, like that in Figure 13.6, which shows a 5-task job that produces a wanted output.

Each task has a probability ( $P_n$ ) of success between 0 and 1, with 1 being certainty and zero total failure. Figure 13.7 shows that within each task there are many individual activities. These also form a series arrangement. When you have a series of activities following each other, where the next activity builds on the work performed by the previous ones, it only requires one error to happen and the whole job goes wrong. To get this job done right the first time requires each of the 25 activities to be done correctly. If one activity in one task is wrong, the job outcome will be wrong and the job will need redoing, possibly even scrapped.

<sup>59</sup> Surowiecki, James., 'The Wisdom of Crowds', Random House, 2004.

What is the chance that all twenty five activities will be done right, and that the whole job is 100% right? The error rate depends on task difficulty and the stress of the situation <sup>60</sup>. Hard tasks not done often have higher error rates. Add stress to the job and the failure rate gets much worse. The reliability of series processes warns us that unless we have great results at every step the job will go wrong. You need to control the chance of error if you want to stop waste and loss.

What has chance got to do with teams and team work? The people in the team work off each other. When a person is uncertain about a decision, they ask other team members for advice. If the team is a mix of subject matter experts, then each is a knowledgeable resource to help one another work with less chance of making error. An example might be an autonomous work team of operators, maintainers and quality control staff in a production department. The maintainer can advise the other team members on equipment reliability issues, the operator has experience in using the production equipment, and the quality control persons can advise on product performance. Each member contributes their best advice and experience to the decision making processes of the other team members. Instead of having one person working alone a team has several people guiding each other in their work. This interaction improves the chance that things will go right more often for everyone on the team.

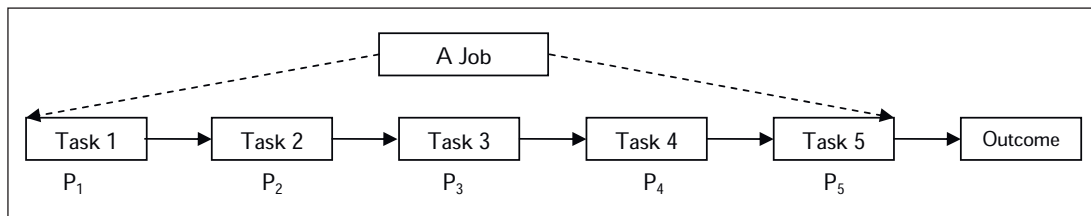


Figure 13.6 – A Series of Tasks are Performed in a Work Process.

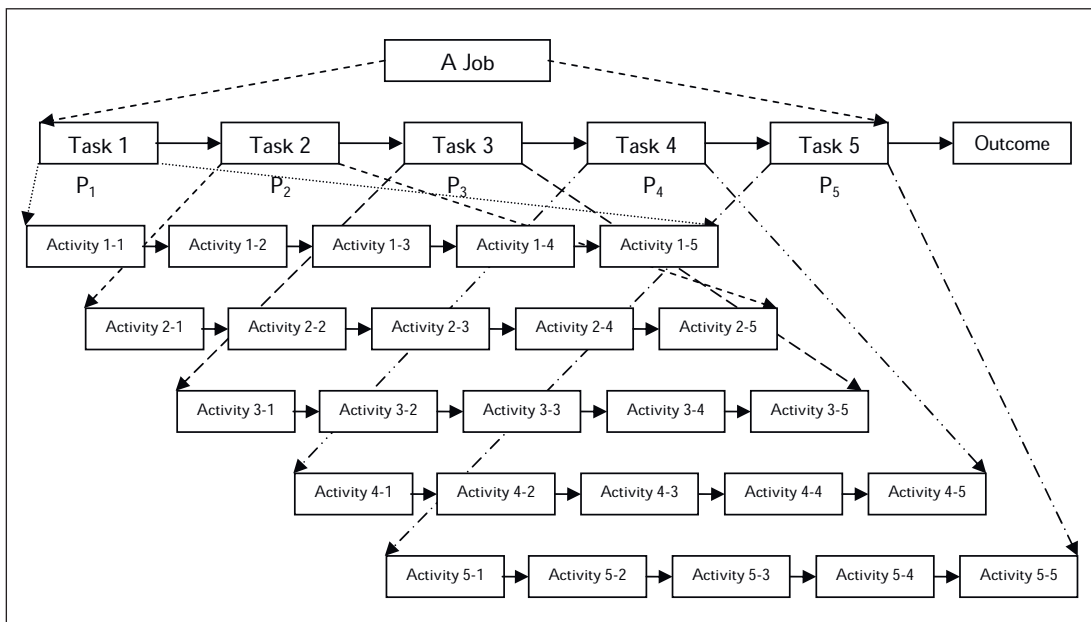


Figure 13.7 – A Series of Activities Occur within Each Task of a Work Process.

<sup>60</sup> Smith, Dr, David J., Reliability, Maintainability and Risk, Appendix 6, Seventh Edition, Elsevier, 2005.

How much difference does a well-functioning team make to the chance of a job going right? Figure 13.8 shows the 5-task job as a team might do it, with everyone helping other team members to get the best result. Person 1 is responsible for doing the work and has support from two others on the team. Each person adds his or her useful contribution at each step. The arrangement of each task is now a parallel activity. This arrangement also has a mathematical formula to work-out the chance that a task will be right. The formula is:

$$P_{\text{parallel}} = 1 - [(1-P_1) \times (1-P_2) \times \dots (1-P_n)]$$

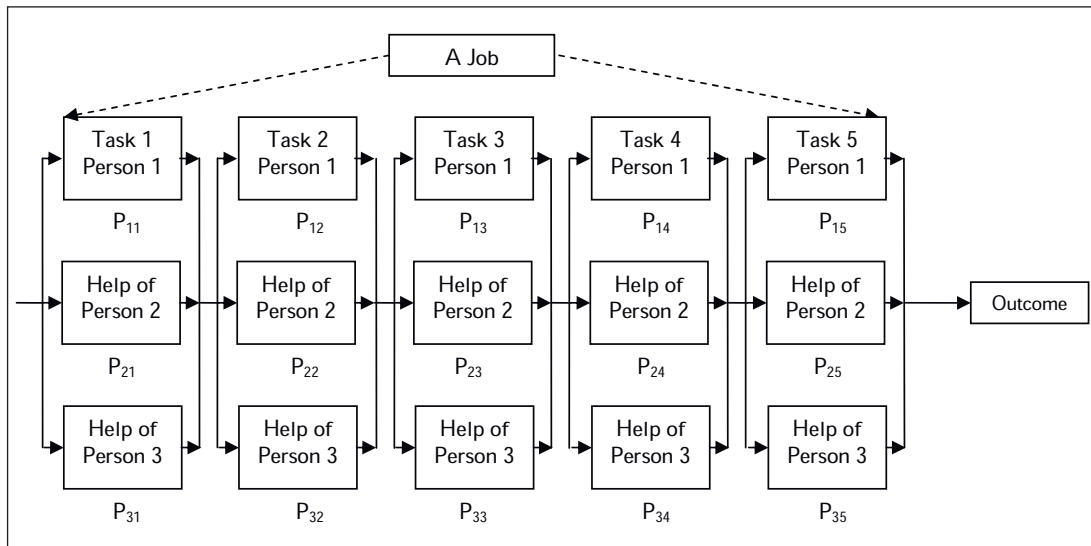


Figure 13.8 – Working as a Team Creates Parallel Teamwork.

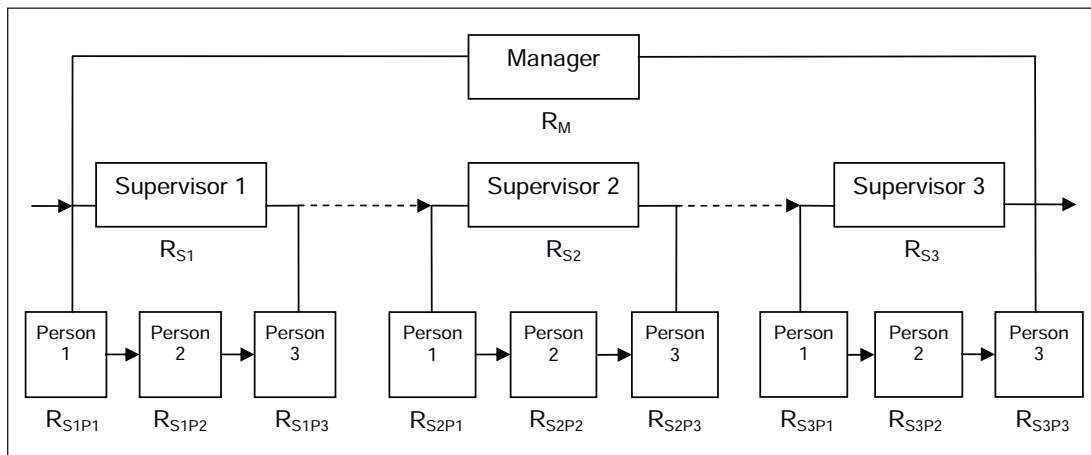


Figure 13.9 – Workplace Silo Groups Formed as Series Structures.

We do not need the formula to see that each task now has three people watching over it. If the person responsible for the work makes an error there are two others helping and checking them. Hopefully one of them will notice any error and correct it. If we were to use the equation, we would find that with three people, each having 90% chance of accuracy, the parallel combination gives us a task that is right 99.9% of the time, and the five task job it is right 99.5% of the time. By paralleling the tasks with a team we have gone from a poor



59% chance of the job being done right with a person working alone, to 99.9% with a team of subject matter experts working together. That is why teams are so powerful. Once people parallel-up in well functioning teams to help each other, the odds of getting better results rises markedly. Teams bring this power to organisations. Teams can help people increase their individual chance of doing outstanding work. They have the ability to greatly improve the odds of delivering right-first-time results. In companies that want high quality, high reliability and fewer risks, a teamwork organisational structure is likely to produce many more favourable outcomes.

How reliable is a cross-functional team structure compared to a silo structure in doing the work? We need to compare the reliability of the silo structure to that of the team structure and see what difference there is. Figure 13.9 is the silo hierarchy drawn as a functional block diagram assuming work is passed from one operator to the next in the work process. For the sake of the example, assume that the people are working in a complicated industrial process without strict quality control making 10 errors in 100 opportunities. This means 90 in every 100 opportunities is done right, a reliability of 0.9. It is about 2.5 sigma quality (3-sigma quality would be 7 errors per 100 opportunities and 4-sigma would be 0.6 errors for 100 opportunities)<sup>61</sup>. The reliability of the silo group process can now be analysed. Starting with the workers doing the series steps, the reliability of the work process is:

$$\underline{R} = \underline{R}_{SIP1} \times \underline{R}_{SIP2} \times \underline{R}_{SIP3} = 0.9 \times 0.9 \times 0.9 = 0.729$$

With a Supervisor paralleled to overview a group, each group's reliability becomes:

$$\underline{R} = 1 - [(1-0.729) \times (1-0.9)] = 1 - [(0.271) \times (0.1)] = 1 - [0.0271] = 0.9729$$

The Supervisor's activity paralleled to the workmen lifts their group's performance. The three groups in the department are in series, each feeding work to the other, and have series reliability of:

$$\underline{R} = 0.9729 \times 0.9729 \times 0.9729 = 0.921$$

With the Manager placed in parallel to manage the operation, the department reliability is:

$$\underline{R} = 1 - [(1-0.921) \times (1-0.9)] = 1 - [(0.079) \times (0.1)] = 1 - [0.0079] = 0.992$$

The department has a theoretic reliability of 0.99 or 1 error in every 100 opportunities – nearly 4-sigma quality. Yet organisations that produce 4-sigma performance are rare. Businesses without a quality control system typically rate 2.5-sigma<sup>62</sup>. Those with a working quality system can be 3 to 3.5-sigma. The assumption of 90% reliability for people doing tasks seems to have been too high because the calculated results do not happen in reality. Let us repeat the calculations with a task reliability of 70% for each individual, or 2-sigma quality of 30 errors in every 100 opportunities.

For the workers doing the series steps, the reliability of their process work tasks is:

$$\underline{R} = 0.7 \times 0.7 \times 0.7 = 0.343$$

With a Supervisor paralleled to overview the work, each silo group reliability becomes:

$$\underline{R} = 1 - [(1-0.343) \times (1-0.7)] = 1 - [0.197] = 0.803$$

<sup>61</sup> George, Mike, et al, 'What is Lean Six Sigma?', McGraw Hill, 2004.

<sup>62</sup> Arthur, J. 'Lean six sigma demystified', McGraw Hill, 2007.

The three work groups are in series and have a series reliability of:

$$\underline{R} = 0.803 \times 0.803 \times 0.803 = 0.518$$

With the Manager placed in parallel to manage the operation the department reliability is:

$$\underline{R} = 1 - [(1-0.518) \times (1-0.7)] = 1 - [0.145] = 0.855 \text{ (about 2.5-sigma quality)}$$

The manager improves the silo structure performance by 65%. The manager and supervisor are key to the success of a silo structure and if their error rate is high, the business suffers badly.

Department output is now 2.5-sigma quality, which is what is expected from a typical business without an inspiring quality system. The difference in results between calculations warns us that poor department performance is the accumulated effect of poor individual task performance.

Figure 13.10 shows a block diagram of the same people in a team structure. The team puts people in a parallel arrangement. Each team is responsible for a process and each person works with 0.7 task reliability. The Supervisors disappear and become team players who coach the workers, while the Manager parallels the teams in their department.

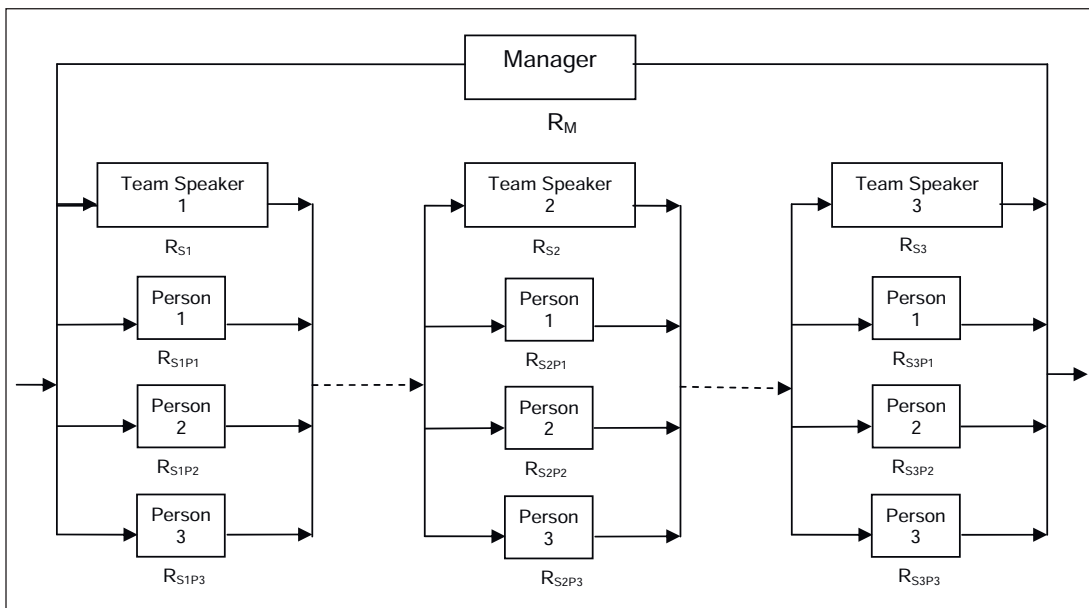


Figure 13.10 – Workplace Groups Teamed in Parallel Structures.

For a team of four people, with each person's reliability at 0.7, the individual team reliability is:

$$\underline{R} = 1 - [(1-0.7) \times (1-0.7) \times (1-0.7) \times (1-0.7)] = 1 - [(0.008)] = 0.992.$$

The three groups work in series, with one feeding its output to the next; a combined reliability of:

$$\underline{R} = 0.992 \times 0.992 \times 0.992 = 0.976$$

When the manager, also at reliability 0.7, is included with the three teams, the reliability of the structure is:

$$\underline{R} = 1 - [(1-0.976) \times (1-0.7)] = 1 - [(0.007)] = 0.993 \text{ (near 4-sigma quality)}$$

Using the same people doing work with 0.7 reliability, the silo structure produced 2.5 sigma quality, while the team structure delivered 4 sigma quality. The manager improved the silo arrangement by 65% for 86% departmental reliability, but in a team structure they improved departmental performance by only by 2% to get 99% departmental reliability. It seems that most of the reliability benefits of a team structure reside with the team and little with the management levels.

The modelling of the silo hierarchical organisation and the cross-functional team structure in the calculations above are not how real organisations actually behave. The examples are constructs for the sake of exploring the effects of each form of structure on the outcomes of an organisation. The investigation indicates that people used in a team arrangement allow the team to produce better results than using those same people in a hierarchical structure. The big assumption is that the people in a team will actually work as a team to get the benefits of a parallel arrangement of functional experts. It means all members and managers are willing to proactively help each other in a spirit of friendship, trust, respect, learning and support for the mutual benefit of all.

Organisations with hierarchical structures seem to have the potential to deliver reliable outcomes, but in reality most perform poorly. Too many times in a hierarchical business the outcomes are wrong. What happens in such organisations to ruin their performance? One possibility is that these companies employ people who are your average guy and girl. These employees simply do their jobs as best they can. Not all of them are experts in what they do and so it is likely that occasional errors are produced from variable quality work. Or maybe each person does the work in their own way because there is no standard method, hence producing a wide range of outcomes, some of which are wrong.

This is another example of the ‘cross-hair game effect’ encountered in Chapter 3 – using a silo organisational structure that cannot deliver the results required, except by luck. Yet some businesses can take the same people and deliver outstanding world-class performance. Choosing the right organisational structure is an important difference. But there is another factor that is even more important than the structure. It is the performance of the organisation’s work quality assurance processes.

## 14. The Accuracy Controlled Enterprise

Our discussions have covered the effects of process variations and the disastrous financial cost of defects and failures. When variation and risk play together businesses tumble, production shuts-down, and people are injured. Are we doomed to play a game of chance every time we go to work? Is hope the only tool we have against variation? Is fluke how we control business process outcomes? Unfortunately, for more, rather than fewer businesses, that seems to be the case. Process confusion and uncontrolled interactions allows variation and risk to thrive inside their organisation. With more processes, and more process steps, comes more opportunity for ruin of one type or another. To combat ever-present variation and risk in business and its processes, quality management systems have developed <sup>63</sup>. Systems such as ISO 9000, Six Sigma and Lean <sup>64</sup> had to be invented to stop variation and reduce failure. In every organisation, from the shopfloor to the corporate boardroom, variation abounds, and only quality management systems can control it.

Hardly anyone ‘gets’ what quality is about. Of the estimated one million companies in the world with ISO 9001 certification in 2008 <sup>65</sup>, few comments are observed in newspapers claiming its great worth to new booming business success. Quality management’s panacea for product excellence is often seen by managers as a wasted effort, sucking-up resources for little business improvement. Yet companies like General Electric, Motorola and Toyota claim that at the root of their success was their quality management system. That success screams that there really ‘is something’ in quality management. There is power in a truly-functioning and inspiring quality management system.

Engendering quality into the use and care of plant and equipment is difficult because it needs committed leadership and much work building better processes, procedures and training systems. That requires overheads for document control, planning of production and maintenance, long-term management of resources and equipment, providing continual training and for the analysis of data to identify problems and discover how to solve them. The cost and effort blinds managers to the great worth that quality systems provide. Instead, maintainers and operators ‘fly be the seat of their pants’ and are expected to get the job done by any means.

### The Precision Principle

Using a certified quality management system is not the only way to get quality. There is no need to have ISO quality accreditation to do an excellent job. Look carefully at how an expert, a total master of their craft, works. There is confidence and certainty in every activity they do. Each act meets specific requirements with great precision. They continually look for evidence that each action is producing the right results. A master craftsman uses accuracy to control variation to a narrow span of outcomes. By being everywhere accurate they do wonderful work. The controlled accuracy that a master craftsman applies needs to pervade a business if they want world-class quality. When the accuracy controlled methods, values and beliefs of the master craftsman is applied by an organisation, they minimise risk, control variation and slash enterprise-wide costs as failures plummet. They become an Accuracy Controlled Enterprise (ACE). The focus in an ACE is not the big-picture product-perfect view of quality. It is just about doing a job, every job, masterly. Whether on the shopfloor or in the boardroom. Every task is done accurately. It is the Carpenter’s Creed used in every work process step.

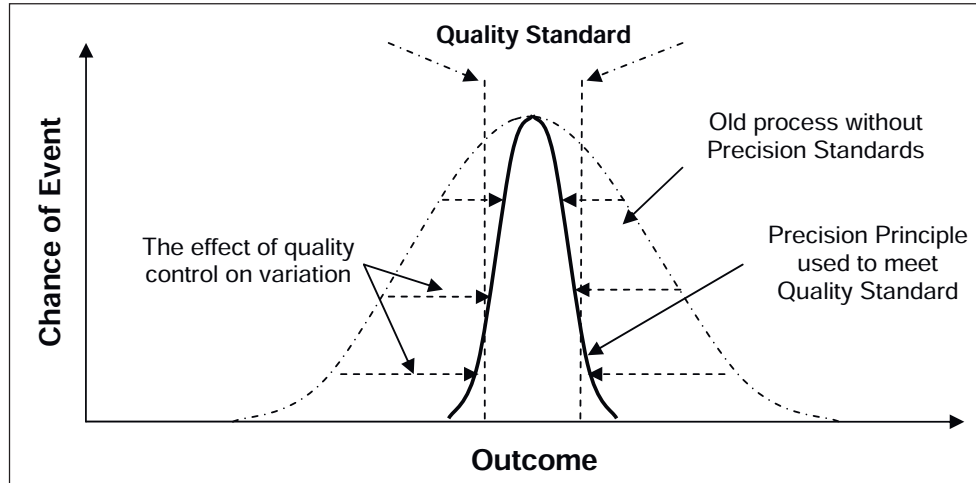
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<sup>63</sup> Hoyle, David, ‘ISO 9000 Quality Systems Handbook’, Butterworth-Heinemann, 5<sup>th</sup> Edition.

<sup>64</sup> Lean is a popular name for the Toyota Production System.

<sup>65</sup> Claimed on International Standards Organisation website, February 2009.

Control over variation and defect creation needs standards of quality to be met. Operations and businesses overcome failure and error with systems guaranteeing precision and accuracy. This is the Precision Principle – set clear and precise work quality requirements. Set standards for every step of a process and measure they are accurately met. A process continually achieving the precision requirements of every step automatically delivers its best quality and throughput. If a process step cannot reliably meet the standards, change its design until it correctly delivers the required result. Figure 14.1 shows what happens when the Precision Principle is applied – first quality standards are set and then the process is improved until the performance meets the standard. By this method the process is sure to deliver successful results.



*Figure 14.1 – The Effect of Controlling Process Step Quality on Variation.*

We encountered a similar process improvement effect in Chapter 7 where W. Edward Deming's PDCA cycle was used to continually redesign a process until it repeatedly delivered the required quality. The Precision Principle is a tool to help you redesign your processes. Start by developing appropriate standards with specific targets, tolerances and measures. Having standards is the key – process improvement starts by setting a target. Performance and quality will follow because the process is changed until the standards are met. Once quality is continually achieved variation naturally stays within the standard because the process is designed to do that. There are far fewer problems and wastes from processes designed to ensure the presence of the skills, equipment, tools and know-how to produce high precision performance.

### **Plant and Equipment Defects, Failures and Errors**

Highly reliable equipment is necessary to reduce production costs and maximise throughput. High equipment reliability requires quality manufacture and precision maintenance, coupled with correct operating practices, which together deliver the necessary controlled conditions that produce high reliability. You get equipment working superbly reliable when designers make the right choices, the maintenance people do their work to precision specification, and operators run equipment so that operating stresses are low. There is no downtime if the equipment design is right for the service, if its parts work in a low-stress environment, and it is operated properly. Highly reliable production is normal and natural when plant and equipment work dependably at long-term sustainable capacity.

If under operation the equipment performance is not as designed then something is amiss. Not with the equipment; the problem is in the business processes, or uncontrolled external agents are at work. Our challenge is to identify the process failures that cause defects and prevent equipment from delivering design performance. Then to act firmly to rectify the situation.

Often the fault for poor equipment reliability lies with the design itself. It can be made of the wrong material for the duty. It may not be strong enough for the stresses induced in it, or the material is incompatible with its environment and degrades. An identified design problem needs design changes to improve equipment reliability. The main reasons equipment does not meet its designed reliability is because it is installed wrongly, it is built or rebuilt poorly, or its parts are allowed to be over-stressed in operation. Usually this happens because people involved in its installation, care and running do not know the right ways.

Though operators and maintainers have training, they can never know enough to handle all situations competently (nor can anyone else know it all). In uncertain situations they use what knowledge they have to make a decision. If what they do works to fix the problem, even if it is the wrong choice, it becomes how they solve that problem again in future. Unfortunately, many decisions do not have an immediately bad effect. If there was it would be good because the person would instantly self-correct and get it right. But most errors of choice do not impact until well into the future. The chosen action has no obvious bad consequences, and since things still run fine, the operator or tradesman, and alas their supervisor, believe it is the right decision. This is how bad practices become set-in-place; through ignorance and misunderstanding.

There is nothing wrong with making a wrong decision. If corrected immediately and nothing bad happens there was no harm done. Bad things happen when wrong decisions progress through time to their natural and final sad conclusion. Regrettably, there are very few decisions that have instant replay options. If it is important in your company to have low maintenance cost and highly-reliable production equipment, then the organisation's work and business systems must support that outcome. All work done by operators, maintainers, engineers and managers needs to be right. There is great value in developing quality systems that help everyone to do their work masterly, right-first-time.

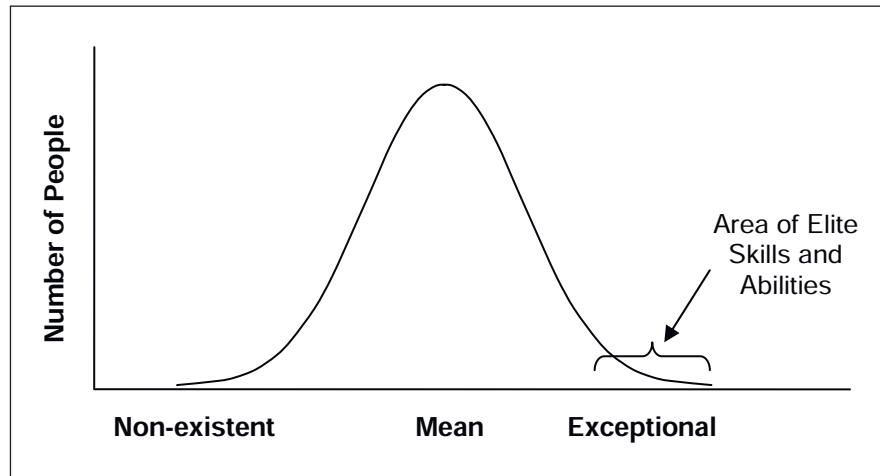
### **Why We Have Standard Operating Procedures**

Variability in work processes leads to defects and failures. Variations in work performance arise because human skills, talents and abilities are typically normally distributed. If we gauged the abilities of a wide cross-section of humanity to do a task, we would end up with a normal distribution bell curve. Secondary and tertiary learning institutions are well aware that student performance follows a normal distribution curve. Figure 14.2 shows a normal distribution bell curve, or Gaussian curve, of a talent in a large human population.

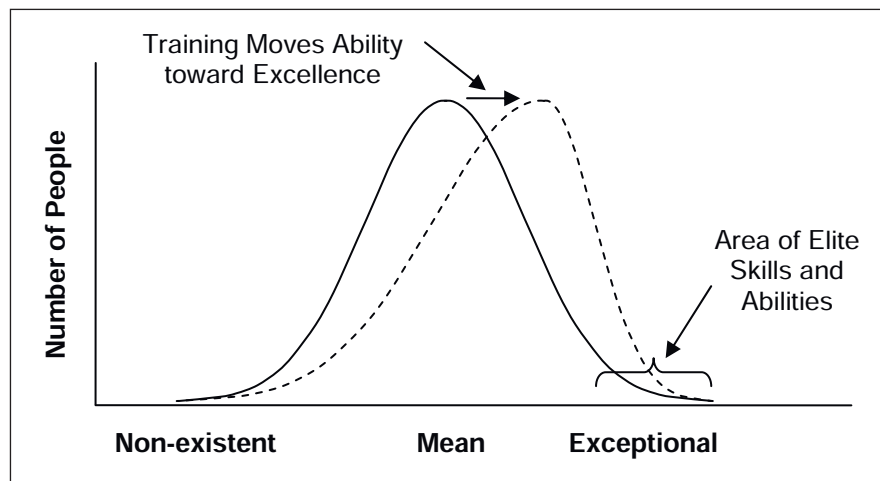
The implication is that for most human skills and talents there are a few exceptional people, a few with astoundingly poor ability and lots in-between clustered around the middle or mean. If a workplace requires highly able people, the distribution curve of human talent warns it will be hard to get exceptional people. The talent distribution curve also explains why continual training of the workforce is so important to a company's long term success. If the available labour clusters around the mean performance level of a skill, then to get better needs additional training in the skill, along with many opportunities to use it. Training and practice has the effect of moving average performers toward the elite end of the population as shown in Figure 14.3 <sup>66</sup>.

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<sup>66</sup> Gladwell, Malcolm, 'Outliers – the story of success', Allan Lane (Penguin Books), 2008.



*Figure 14.2 Distribution of a Talent in the Human Population.*



*Figure 14.3 – The Effect of Training on Developing a Talent.*

### **The Cost of Poorly Written Standard Operating Procedures**

A job or operating procedure is a written systematic approach to a task that should provide clear guidance, set the required standard and stop variations in work performance. Standard operating procedures allow people from around the middle and below ability levels to do higher standard work than they naturally could do unassisted. Since standard operating procedures (SOPs) control the quality of the work performed by people not expert in a task, they are critical to the proper running of a business. Companies have long recognised that reproducible, correct results from the workforce need a proven and endorsed job procedure. It is also critically important that they are written in ways to promote maximum efficiency and make use of the least resources, while being effective at getting a task done in the fastest correct way. In the Author's workplace experience very few companies use SOPs to control production outcomes. When they are available they typically only record what to do in a task, are not self-checking and do not promote good practices. The better SOPs explain how to do the task, but most SOPs offer little practical assistance to the user in controlling product quality, or the quality of their performance in doing the task. Typically, an SOP is glanced over when operators and maintainers start a new job and then thrown to the back of the shelf.



That is a pity because they are one of the most powerful learning tools ever developed for use in the workplace.

Of the companies that have SOPs, an expert in the job most likely wrote them. They wrote the procedure already knowing all the answers. So they described tasks assuming prior knowledge. You will often see in SOPs statements such as – “Inspect lights, check switch, check fuse, and test circuit”, and “Inspect drive linkage for looseness”. Or in the case of a machine operator – “Test the vehicle and report its condition”. The problem with the use of procedures containing such descriptions is that you must first be an expert to know whether there is anything wrong with what you are looking at. Procedures without all the correct details require hiring trained and qualified people to do what may be a very simple job.

### **The Best SOPs Can Be Done By the Least Skilled People**

Great SOPs are those that ensure workmanship quality. They contain detail and guidance, they include a target to hit, a tolerance on accuracy and regular proof-tests of compliance to guarantee job quality – they deliver masterly performance. In this way, they prevent defects from arising and so prevent future failures. With hands-on training and workplace experience even non-experts can do them well.

Standard operating procedures are quality and accuracy control devices with the power to deliver a specific level of excellence every time they are used. Few companies understand the true power of an SOP. Typically they use them because the company’s quality system demands it. People mistakenly write them as fast as they can, with the least details and content necessary to get the document approved. In reality SOPs save time, money, people and effort because they can make production outstandingly reliable by eliminating defects. They can prevent plant and equipment failures and so boost productivity.

Accuracy is the degree of conformity of a measured or calculated value to its actual or specified value. To be accurate requires a target value and a tolerance of what is acceptably close to the target. For a standard operating procedure to have powerful positive effects it needs clear and precise Targets, Tolerances and Tests – the 3Ts of masterly work – which if faithfully met will produce the required outcome.

The problem with targets is that they are not easy to hit dead-centre. If a procedural task states an exact result, then it has asked for an unrealistic outcome. A target requires a tolerance range within which a result is acceptable. There must be upper and lower limits on the required result. Even the bulls-eye in an archery target is not a dot; it is a circle with a sizable diameter. The bulls-eye in Figure 14.4 is not a pin head in size. Anywhere within the bulls-eye gets full marks. The target for each task in an accuracy-controlled procedure must have a tolerance.



*Figure 14.4 – Targets & Tolerances.*

Great equipment reliability and production performance naturally follows when doing work to operating procedures using the 3Ts. Figure 14.5 shows what accuracy means and how the 3Ts are used to get it. The 3Ts act to remove work variability. They create statistical process control over human activity. 3Ts put into procedures standardise performance and deliver repeatable outcomes. Instead of having a wide range of possible results the 3Ts limit the results to those you specify.

If we take the poorly specified “Inspect drive linkage for looseness” requirement from above, and apply the ‘target, tolerance, test’ method, a resulting description might be: “With a sharpened pointed pencil mark a straight line on the coupling and shafts of the linkage as shown in the accompanying drawing/photo (A sketch or photo would be provided, and if necessary also describe how to mark a straight scribe mark). Grab both sides of the linkage and firmly twist in opposite directions. Observe the scribe marks as you twist. If they go out of alignment more than the thickness of the scribe mark replace the linkage (a sketch would be included showing when the movement is out of tolerance).” The procedure would then continue to list and specify any other necessary proof-tests and resulting repairs. With such detail provided it is no longer necessary to use highly qualified persons for the inspection. Anyone with mechanical aptitude can do reliable work once they are trained. Like a motor car manual for novice mechanics, top-class procedures are written with detailed descriptions and plentiful vivid images. Once novice mechanics have such manuals in-hand they can do a lot of their own maintenance with certainty of job quality. If procedures contain all the information and measures necessary to correctly rebuild equipment, or to run a piece of plant accurately, people with average skills can do the job well.

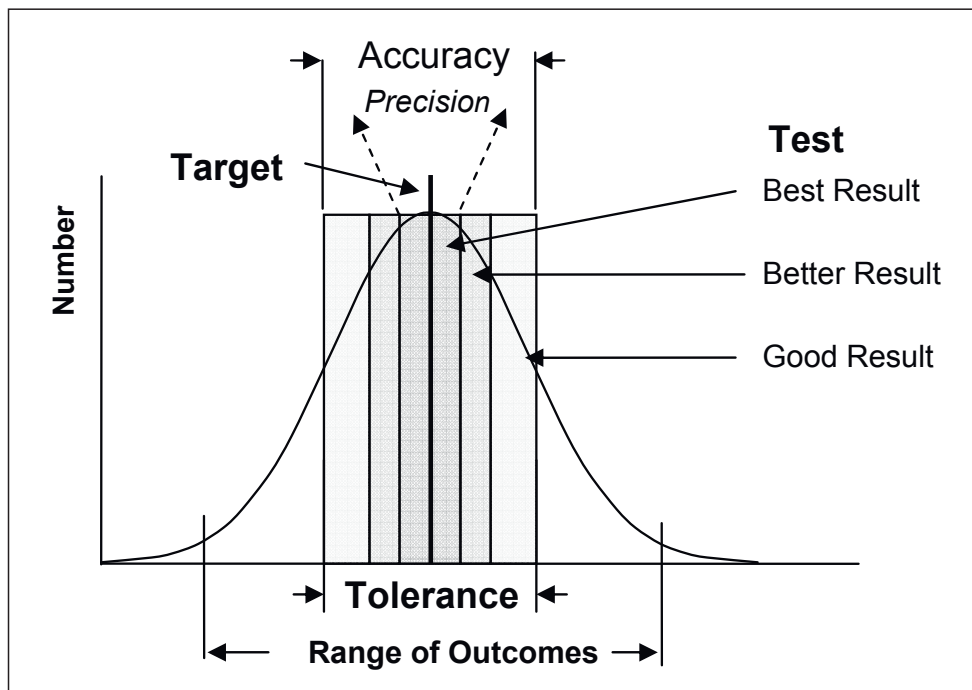


Figure 14.5 – Accuracy Control and the 3Ts – Target, Tolerance, Test.

Improving the accuracy of a task is done by using well-formulated, clearly understood standard operating procedures that contain targets to hit, tolerances for acceptable closeness and tests to prove the work is to the required accuracy. When there are high cost consequences, the first thing to do is to introduce improved SOPs to control the work variability and risk. The inclusion of ‘target, tolerance, test’ – the 3Ts of defect elimination – in all procedural tasks is the first rule of failure prevention. The only better solution is to error-proof so a mistake does not matter.

### ‘Good, Better, Best’ Tolerance Banding

You can drive continuous improvement in job quality by dividing the tolerance you place about a task target into ‘good, better, best’ tolerance bands. The bands specify levels of precision. Figure 14.6 shows tolerance banding used to challenge people to deliver high quality work.

Competent people are expected to continually achieve ‘best’ quality results. People developing their skills meet ‘better’ levels of performance. Novices are permitted to do the task to ‘good’ levels of accuracy. Using tolerance banding provides clear indication of what is high quality work and recognition of its achievement. Application of ‘good, better, best’ scales naturally challenges everyone to try and become ‘the best’. It is a simple psychological tool to improve work quality.

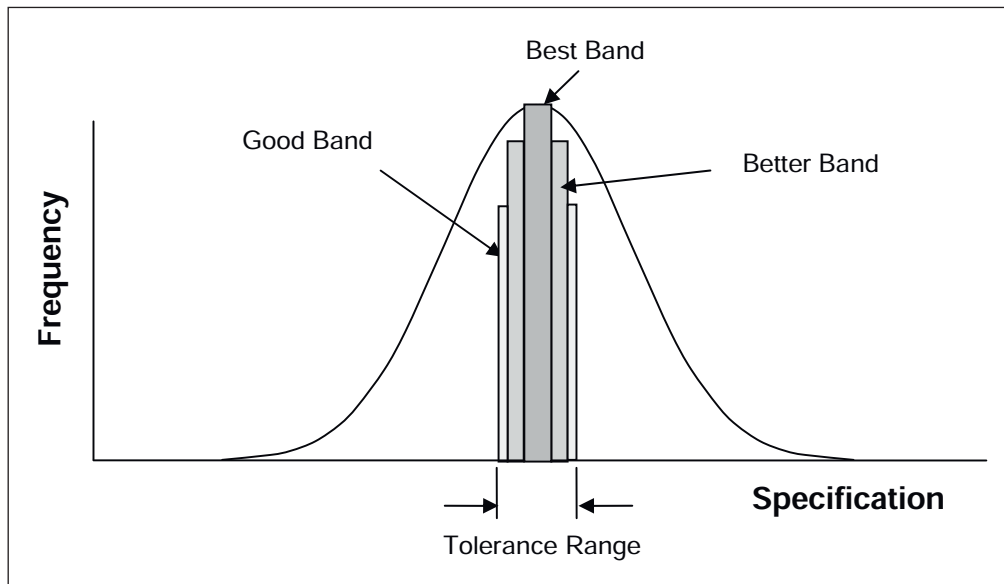


Figure 14.6 – Controlling Work Quality with ‘Good, Better, Best’ Tolerance Bands.

### Train and Retrain Your People to Your Standard Operating Procedures

Having a procedure full of best content and excellent explanations for your workforce is not by itself enough to guarantee accuracy. How can you be sure that people comprehend what they read? Many tradesmen and plant operators are not literate, nor do they understand the true meaning of all the terms used in a procedure. To be sure your people know what to do, and can do it right, they need training and practice in the procedure. They need to know how to do the work thoroughly before they are allowed to do it unsupervised. Later they will need regular refresher and reinforcement training. The amount and extent of training varies depending on the frequency use, the skill level of the persons involved, and their past practical experience in successfully doing the work.

Procedures done annually or more often by the same people usually do not need retraining unless they are complicated, or carry great inherent risk. Because people forget, those procedures on longer cycles than annually will need refreshment training before they are next done. Training and retraining often seems such an unnecessary impost on an organisation. Managers often say, “If the work is done by qualified people why do I need to train them? They have already been trained.” The answer to that question is “How many defects, errors and mistakes are you willing to pay for? What risks are you willing to carry in your operation?” If organisational risk management systems use procedures to protect the organisation from risk it is necessary to continually check and prove the protection layer is in place and operating

properly. Training, retraining and auditing actual hands-on performance helps to keep that protective layer whole. Assuming that people can be ‘trained once, trained for life’ is a serious error of judgement. For example, if a flange leaks soon after rebuilding a piece of equipment, it is a sign that you may need to retrain your people in the correct bolting of flanges. Flanges squarely mounted, in good condition, and properly rated for the service do not leak if they are bolted-up right. When a repair re-occurs often on perfectly good equipment it is a sign that the SOP does not contain targets, tolerances and proof-tests, or the procedure is laying at the back of a shelf somewhere and people need training.

### **Making Your Organisation an ACE**

A classic example of what great value an accuracy-focused SOP can bring is in this story of a forced draft fan bearing failure. The rear roller bearing on the fan never lasted more than about two months after a repair. The downtime was an expensive and great inconvenience. To prevent a breakdown the bearing was replaced every six weeks during a planned outage and also put on vibration analysis observation. After several replacements enough vibration data was collected to diagnose a pinched outer bearing race. The rear bearing housing had been machined oval when manufactured and it squeezed the new bearing out-of-round every time it bolted up. You could say that vibration analysis did wonderfully well. But the truth is the repair procedure failed badly. If there had been a task in the procedure to measure the bolted bearing housing roundness and compare the dimensions to allowable target measurements, they would have found the oval-shaped hole at the first rebuild. There was no need for the bearing to fail after the first time. A badly written procedure had failed the organisation. Whereas an accuracy-controlled procedure with targets, tolerances and proof-tests would have found the problem on the first repair, and fixed it permanently.

Existing ISO 9000 or Six Sigma quality procedures convert to accuracy-controlled operating procedures with little development cost. The only extra requirement is that they include a target with tolerances and a proof-test in every activity to give feedback and confirmation that each task is done right as the job progresses.

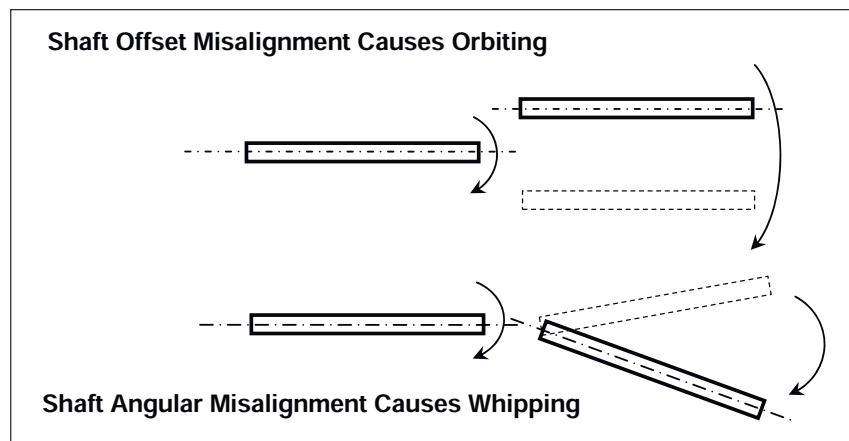
A well written accuracy-controlled procedure contains clear individual tasks; each with a measurable result observable by the user and a range within which the result is accepted. With each new task only allowed to start once the previous one is within target it is possible to guarantee a top quality result. With targets in the procedure, its user is obliged to perform the work so that they are within the required tolerance. Having a target and tolerance forces the user to become significantly more accurate than without them. With all the task targets hit, the procedure is done accurately and excellent work results. The 3Ts automatically build defect elimination into a job.

Once a procedure always delivers its purpose you have developed a failure control system. No longer will unexpected events happen if work is done accurately to the requirements of the procedure. The procedure guarantees in-built accuracy that prevents failure and stops the introduction of defects.

To ensure each task is correctly completed the worker is given a measurable target and tolerance to work to. The procedure is correct when its individual tasks are all within their target limits. Using this methodology in standard operation procedures makes them quality control and training documents of outstandingly high value. Those organisations that use sound failure control and defect prevention systems based on proof-tested, accurate work, move from being a quality conscious organisation to being an accuracy-controlled enterprise; an ACE organisation. With 3T accuracy in maintenance, operation and engineering tasks, getting outstanding equipment reliability and consistently high production performance becomes normal.

## The Value of Precision

The need for precision and accuracy to control variability dominate those industries that use plant and equipment. It is the most critical requirement for high reliability. Industries using machines require them to run reliably (no failures or unplanned stoppages) with high availability (ready for immediate use) and high utilisation (continuously in use) all their working life. Outstanding reliability, availability and utilisation come from being precise and accurate in equipment assembly and use. Precision and accuracy in equipment design, construction, operation and maintenance is a sure way to achieve a lifetime of high equipment performance and service with low operating costs. But it requires the patience to develop the skills and dedication to continually apply accuracy control, for its achievement. Man-made equipment and machinery only work well for a long time when they work precisely. Precision means meeting specified standards to within allowed tolerances. Precision requires that the specific standards needed for high reliability are set and continually achieved during design, manufacture, assembly, operation and maintenance. Accuracy is the lifeblood of equipment reliability. Precision results from controlling accuracy. An example of precision is the alignment between two rotating shafts shown in Figure 14.7. If two shafts are off-set to each other they run out-of-true, distorting each other and causing massive forces to be loaded onto the bearings and coupling. Eventually the bearings, coupling or shafts are destroyed because of the inaccuracy in their alignment.



*Figure 14.7 – Inaccurately Aligned Shafts Destroy Machinery.*

The two shafts must align with sufficient accuracy to ensure they run without creating destructive forces. When an accuracy standard is set a requirement is established which must be confirmed by measurement. For example, an alignment standard for the two shafts in Figure 14.7 rotating at 1500 RPM is to require their axial parallel offset be aligned to better than 0.025mm (0.001”) per 100mm of coupling separation and angular alignment to be better than 0.06 degrees<sup>67</sup>. The standard specifies the accuracy needed to meet engineering design requirements. The positions of the shafts can now be measure and adjusted until they are precise. Introducing accuracy standards into workplace methods ensures the precision that prevents defects. This translates into highly reliable equipment with outstanding availability and reliable performance.

<sup>67</sup> Piotrowski, John, 'Shaft Alignment Handbook', CRC Press, Third Edition, 2007.

## **Senior Managers are the Leaders of ACE**

An Accuracy Controlled Enterprise is not the same as an enterprise with a quality management system. Quality management imposes control over the processes, people and equipment that affect the quality of a product. ACE is subtly different because it is about instilling excellence into work; it's about helping people to be great. From the most senior person to the least, the philosophy requires that people know what an excellent outcome is in every task they do, and they strive to achieve 'good, better, best' results. An ACE has clear targets, tolerances and tests in procedures for senior management as well as for shopfloor personnel. Senior managers show leadership by placing the requirements of ACE on themselves first. They show how the 3Ts of defect elimination improve their own performance before they take ACE into the organisation. Unlike quality management systems, where senior managers place the quality demands on those below them in the organisation and monitor their performance from above, the Accuracy Controlled Enterprise focuses on individual excellence and allows managers to lead their people by example. The 'leading from the front' required for successful ACE adoption is a very powerful symbol of management commitment to improving the organisation and helping its people.

Figures 14.8 and 14.9 represent the business aims of Accuracy Controlled Enterprise work quality assurance. ACE drives quality improvement by making people responsible for the quality of their performance. It helps people to achieve precision in their workmanship by providing clear targets to meet, certainty about what is 'good enough' and a means to prove for themselves that they are doing quality work. It encourages them to improve their skills. They can even change and improve the job design and make it simpler and easier.

## **Examples of an Accuracy Controlled Procedure**

Accuracy controlled procedures are simple for users but have demanding requirements for writers. ACE procedure writing starts with drawing a flow map of the procedural steps. The flow chart is in landscape orientation and formatted as shown in Figure 14.11 for specific reasons. The across page flow makes the process easy to visualise. Each process step box is given a brief descriptor. Reading the descriptors explains the substance of the procedure. Drop boxes below each process step box add information and explanation. The layout also makes it easy to conduct Lean Value Stream Mapping and Process Step Contribution Mapping in future.

Be clear about the importance of the procedure to the business, identify its purpose, and indicate the people affected by the work and the necessity of doing it thoroughly and correctly. This helps to establish the right mindset in the user to want to do excellent work in a timely fashion.

An accuracy controlled procedure incorporates the 3Ts of defect elimination – Target, Tolerance, and Test – in each procedural task. This provides statistical process control and allows users to identify clearly the requirements they need to meet. They check themselves that they have met each requirement before going to the next task. Explain every step in a task in simple detail using both words and images. Define and explain the information flows and the records needed. Write the SOP with the intention of using it as a record of the task and a quality control form.

An ACE 3T procedure layout is shown in Figure 14.10. The Target is shown in the 'Best' column, the Tolerance is subdivided into 'Good, Better, Best' ranges, and a Test is specified for each task. The two-sided standard of an ACE 3T procedure is far superior to a single-sided accept/reject criteria. A single-sided criteria tells you how bad you can be. But a two-sided criteria tells you how good you need to be.



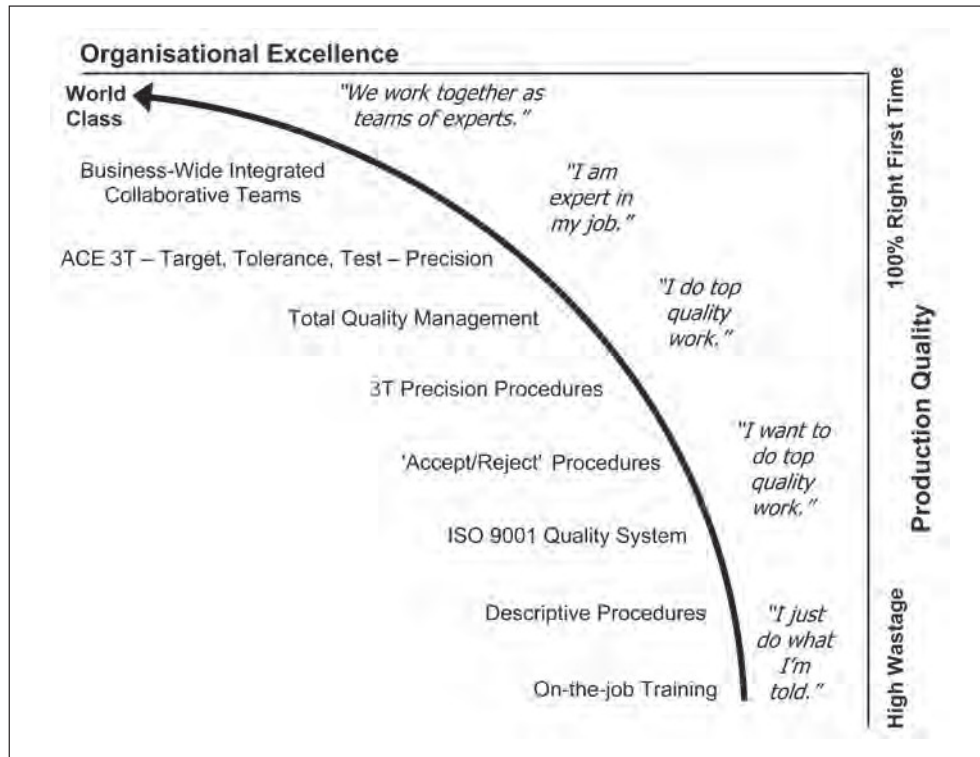


Figure 14.8 – The Quality Culture of Plant and Equipment Wellness.



Figure 14.9 – The People of Plant and Equipment Wellness.



Task Step No	Task Step Owner	Task Step Name	Materials, Tools and Their Condition	Full Description of Task	Test for Correctness	Tolerance Range			Record Actual Result	Action if Out of Tolerance	Sign-off After Complete
		(Max 3 – 4 words)		(Include all tables, diagrams and pictures)	(Include diagrams and pictures)	Good	Better	Best			
1	2	3	4	5	6	7	8	9	10	11	12

*Figure 14.10 – An ACE 3T Procedure Layout.*

Two examples of an ACE procedure follow. The first is for a clerical task and sets accept/reject criteria for each activity. The second procedure, for bolting-up a pipe flange, is in the full ACE 3T format. Notice how the procedures specify the standard and quality that must be achieved on the job. The workmanship quality and standard of work is not left to the discretion of the person doing the work. As a minimum, each task step has an ‘accept/not accept’ standard. In the case of the ACE 3T procedure, it clearly states the minimum acceptable outcome, called ‘good’, and identifies the top-class performance in the ‘best’ column. The ACE 3T approach provides a practical and sure way to control work quality regardless of who does the job. Now everyone knows what ‘good enough is’ and anything less is unacceptable. Everyone also knows what top-class work is and are encouraged to strive for it.

### **Clerical Pass/Fail Example – Cost Report Spreadsheet Procedure**

This procedure explains in detail how to create the department’s monthly production costs summary spreadsheet. The department manager and the cost accountants use this spreadsheet to make their monthly business performance reports. Any errors in the spreadsheet will flow through to the monthly report presented to head office.

This procedure is our current best practice and you should follow it exactly. It is the result of many people’s efforts over many years. It is the quickest, best way yet found to do the job. You are encouraged to learn the job exactly as in this document. If after you master this procedure exactly, you believe that you know of improvements, please bring them forward for discussion. You can test your ideas and compare them to the procedure. If your suggestion proves to be better, it will become the new way of doing this job.

### **Necessary Equipment and Tools**

Computer, National Monthly Production computer file, National Monthly Production hardcopy file

### **Task Summary**

A summary of the process for completing the spreadsheet is below. A fully detailed procedure is beneath the list. If you have a problem that you cannot solve please see your supervisor.

1. Find spreadsheet
2. Bring up spreadsheet
3. Select work sheet
4. Get hardcopy folder
5. Return with hardcopy
6. Record monthly total
7. Cross check totals
8. Totals don’t agree
9. No spread-sheet error
10. Hardcopy checked
11. Update spreadsheet
12. Totals agree

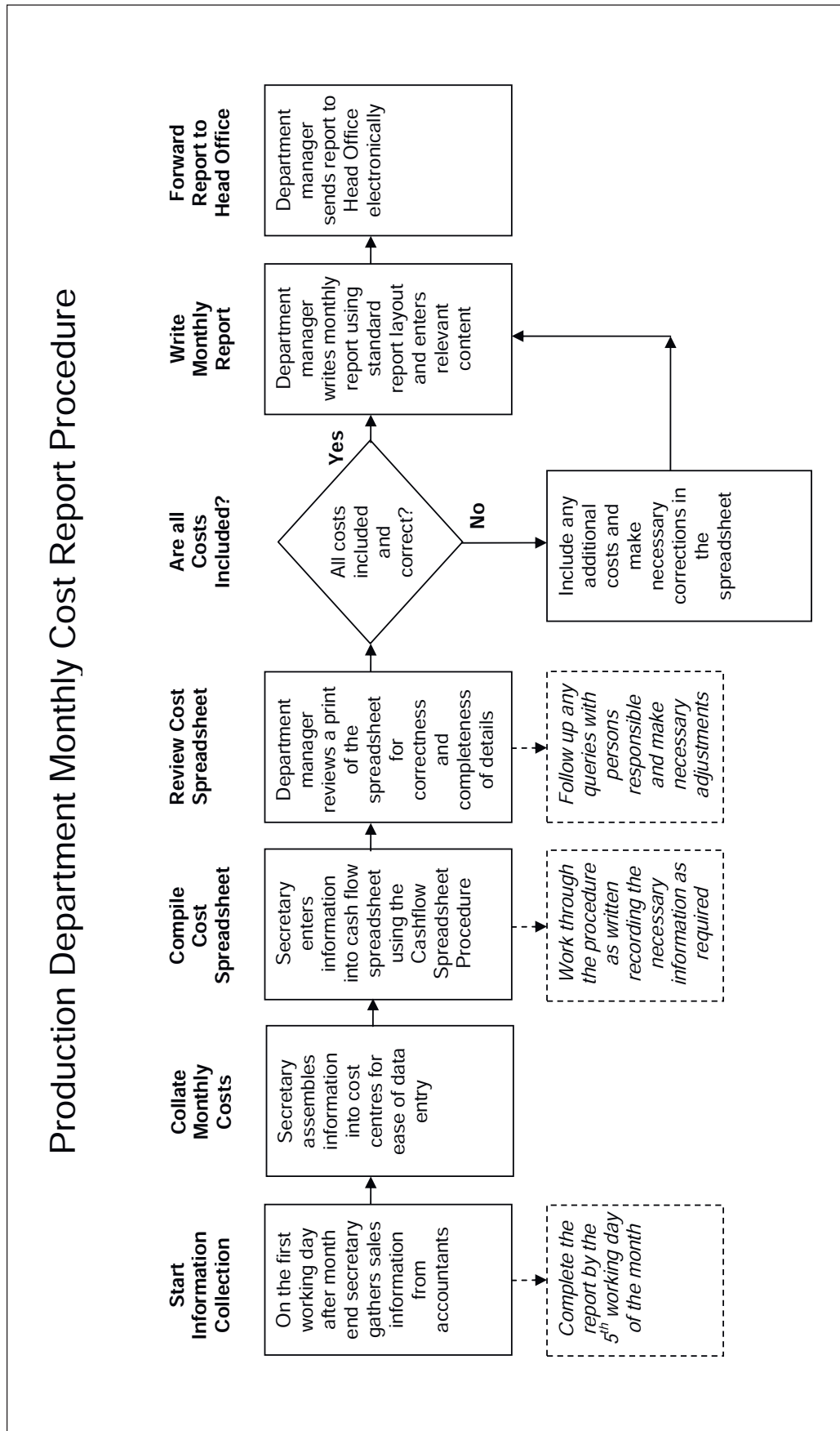
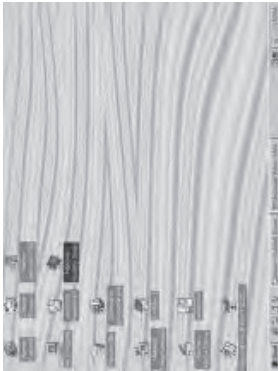
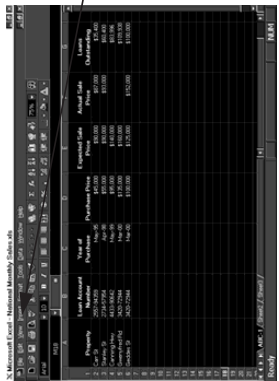
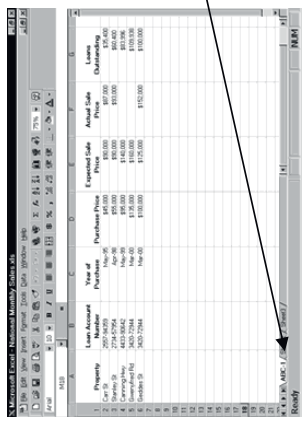
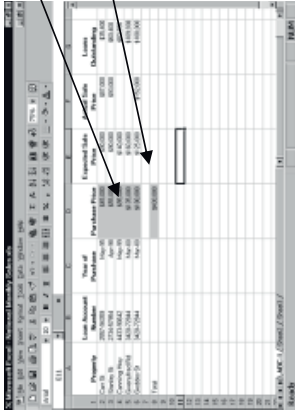


Figure 14.11 – Process Flow Map of Cost Report Procedure.

Task Step No.	Task Step Owner	Task Step Name	Full Description of Task	Test for Correctness	Record Actual Result	Initial After Complete
1.	Office clerk	Find spread-sheet	Find the shortcut on the screen called 'National Monthly Production'. 	See the icon called 'National Monthly Production'.		
2.	Office clerk	Bring up spread-sheet	Make spreadsheet 'ABC' active on computer by 'double-clicking' the icon. 	Note the name on the spreadsheet is 'National Monthly Production'.	(Place spreadsheet name here.)	

Task Step No.	Task Step Owner	Task Step Name	Full Description of Task	Test for Correctness	Record Actual Result	Initial After Complete
3.	Office clerk	Select work-sheet	Bring up the worksheet called 'ABC-1' to use. 	See the name on the SOP and actual worksheet is 'ABC-1'.	(Place worksheet name here.)	
4.	Office clerk	Get hardcopy folder	Get the 'National Monthly Production' folder in the top draw of the National Sales filing cabinet in the Sales Office.	Read the file name and see it is called 'National Monthly Production'.		
5.	Office clerk	Return with hardcopy	Return to your desk and open the folder to the Total National Production Report.	See that the page has the title 'Total National Production Report'.		
6.	Office clerk	Record monthly total	Total the 'Purchase Price' column for the month and put into cell 'D8'.	Check cell 'D8' has the monthly total.	(Could also record monthly total here.)	
7.	Office clerk	Cross check totals	Check that the total for 'Purchase Price' in the hardcopy folder and the spreadsheet are the same.	Both totals are the same.	(Record the total.)	

Task Step No.	Task Step Owner	Task Step Name	Full Description of Task	Test for Correctness	Record Actual Result	Initial After Complete
8.	Office clerk	Totals don't agree	<p>If the two numbers are not the same, check the formula in the spreadsheet matches the cells that it should.</p> 	Check all individual cells are picked up by the formula in the Totals cell.		
9.	Office clerk	No spreadsheet error	If the spreadsheet is correct, the error lies in the hardcopy file. Report the error by telephone to the Manager National Production.	Ring the National Manager.		
10.	National Production Manager	Hardcopy checked	Confirm the totals of individual sales are recorded correctly and ring back the correct individual production figures.	National Managers advises each figure.		
11.	Office clerk	Update spreadsheet	Correct the figures in the spreadsheet with the correct values and confirm the totals are now correct.	Double check the new total against hardcopy file total.	(Record the correct total.)	
12.	Office clerk	Totals agree	If the totals in both documents agree, the job is complete. Save the spreadsheet, print a copy for the manager to review, close the electronic file and return the hardcopy file to the office filing cabinet.	See spreadsheet is saved and file returned.		

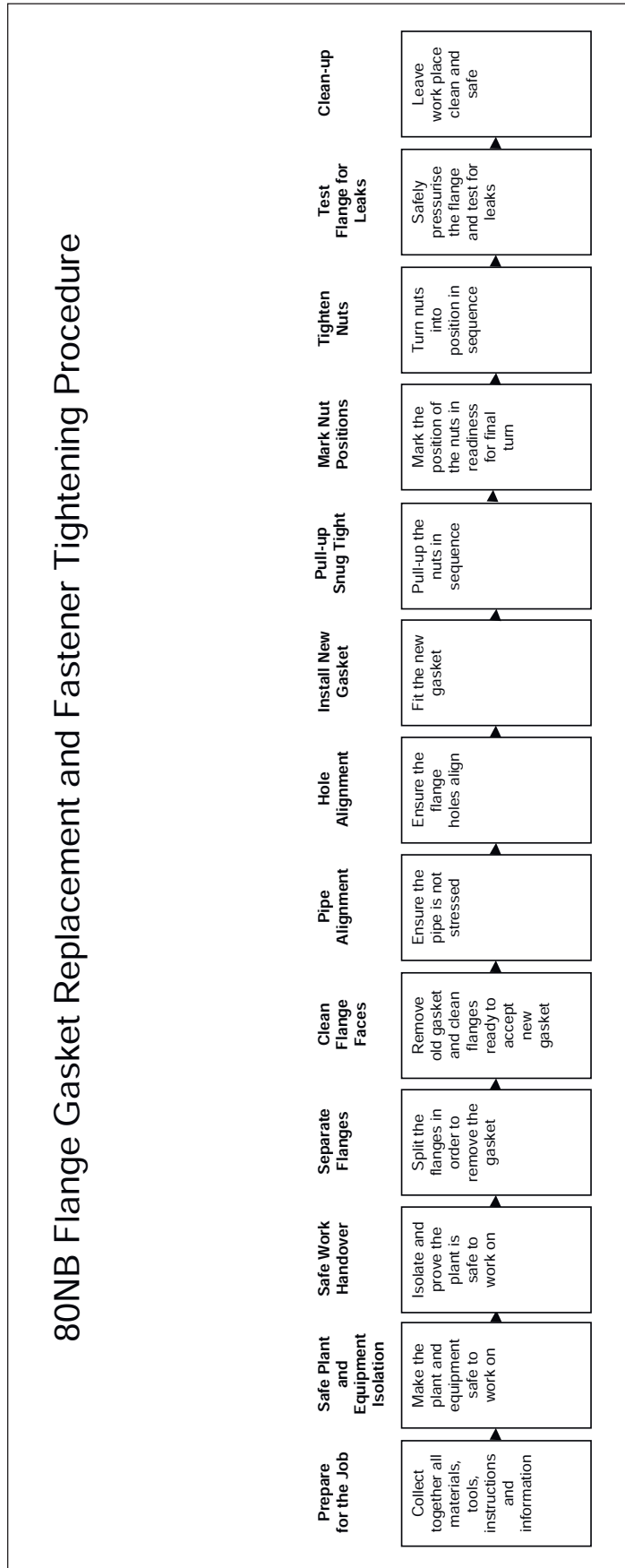


Figure 14.12 – Process Flow Map of Flange Connection Procedure.

### ACE 3T Example – Flange Connection Procedure with Tolerance Banding

This is a partially complete example of an Accuracy Controlled Enterprise (ACE) 3T procedure with tolerance bands to bolt together 80 NB, ANSI B36.5, forged steel, Class 150 flanges. Each task has a target with the allowed limits banded into ‘good, better, best’. Provide instruction if the tolerance is not achieved.

**NOTE:** *The example covers the method to use to create a 3T procedure and is not the actual procedure to use when bolting-up flanges. Each organisation must research, develop and approve their safe practices and procedures for bolting flanges. The use of turn-of-nut on pressure flanges may not comply with the applicable pressure piping design codes.*

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### Flange Connection Procedure

*Importance of correctly mating flanges:* This procedure explains how to bolt-up correctly a pipe flange on 80mm (3”) diameter pipe. Leaks of dangerous chemicals from pipe flanges create a safety and environmental hazard that can lead to death of workmates and the destruction of production plant and equipment. Even a water leak from a flange causes slip hazards and makes an unsightly mess. Pipe flanges must be bolted-up so they never leak.

This procedure is our current best practice and you should follow it exactly. It is the result of many people’s efforts over many years. It is the quickest, best way yet found to do the job. You are encouraged to learn the job exactly as in this document. If after you master this procedure exactly, you believe that you know of improvements, please bring them forward for discussion. You can test your ideas and compare them to the procedure. If your suggestion proves to be better, it will become the new way of doing this job.

Necessary Equipment and Tools: Gasket, ring spanners (do not use adjustable shifters and pipe wrenches as they damage corners of bolt heads and nuts making their removal dangerous and unsafe), suitably load-rated studs and nuts, pencil.

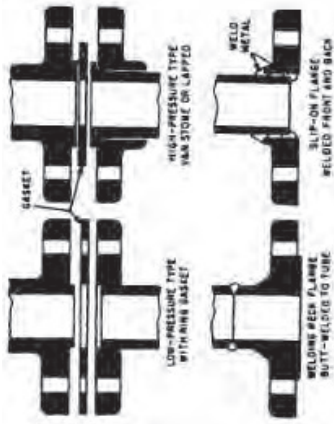
### Task Summary

A summary of the process of installing gaskets and making flanges is below. A fully detailed procedure is beneath the list. If you have a problem that you cannot solve please see your supervisor.

- |   |   |
|---|---|
| 1. Get work pack, tools, NEW fasteners and NEW gasket | 7. Check and correct bolt hole alignment                                    |
| 2. Get safe handover isolated and pipe drained        | 8. Mount gasket and insert fasteners  |
| 3. Place personal danger tags test if drained         | 9. Pull-up fasteners snug tight in sequence                                 |
| 4. Break and spread flange safely                     | 10. Mark nut position and turn angle past snug                              |
| 5. Clean-up flange faces                              | 11. Turn nuts to position in sequence                                       |
| 6. Check and correct unrestrained pipe alignment      | 12. Test flange for leakage at operating pressure                           |
|   | 13. Safely clean-up, hand-back, complete job record and sign-off Work Order |



Bolt Size	Bolt Grade	Bolt Torque	Tolerance on Torque
5/8"	A193 B7 stud and nut	201 Nm (60% Yield)	+ - 25% with Torque Wrench
		½ turn from snug tight	Between ½ to 5/8 <sup>th</sup> turn
<b>Gasket:</b> Non-asbestos fibre, 1.5 mm thick, ring, grade as noted on work order			





### Engineering Standards

**Flange Squareness:**  
 Good: Within 1mm for every 200mm diameter  
 Better: Within 0.75mm for every 200mm diameter  
 Best: Within 0.5mm for every 200mm diameter

**Stress-free Flange Bolt Hole Alignment:**  
 Good: Centres within 2mm  
 Better: Centres Within 1.5mm  
 Best: Centres within 1mm

**Bolt Lubricant:** Molybdenum disulphide

Task	Task Step Owner	Task Step Name (Max 3 – 4 words)	Task Description	Mat'l – Tools and their Condition	Test for Correctness (Include diagrams and pictures)	Good	Better	Best	Reading / Result	Action if Out of Tolerance	Sign off
1	Technician	Prepare for the job	Gather together NEW studs and nuts, washers gasket, thread paste, tools, job work order, danger tags, handover permit, special instructions, PPE	5/8" ring spanner or socket, podgy spike bar, screw driver, scraper	All materials and tools are on the job before starting the job	Request and collect issued items from store	Planner arranged all items ready for issue from Store	Planner has all items at job and job is ready to do		Only start work once all requirements are gathered together	
2	Technician	Inform operator	Contact Operations personnel responsible for plant isolations and handover		Handover preparation and documents correctly done	Contact Operator when ready to start job	Operator has plant off-line awaiting work	Operator has plant isolated, tagged and drained		Job can only start when Operations safely handover plant and piping	
3	Technician and Plant Operator	Make work place safe	Place personal danger tags at isolation points and accept plant handover after proving isolations and drainage	Danger Tags	Isolation procedure is correctly done and proven safe	Operator and repair man walk circuit and identify and tag isolations and open drains	Operator has isolated plant & tagged isolations out-of-service & drained piping	Operator provides isolation point drawing and walks circuit to show previous tagged isolations and open drains		Only start work when piping is fully drained and proven to be empty and possible gas build-up vented	
4	Technician	Separate flanges	Release tension on exiting fasteners gradually in tightening sequence and then remove one fastener at a time but leaving the last fastener loosely in place if pipe springs unexpectedly, spring flanges with podgy bar	5/8" ring spanner or socket, anti-seize liquid	All fasteners removed without damage to flanges or harm to personnel or other property	Back-off all nuts half a turn in sequence and then a full turn, removing all fasteners but last one. Spring flanges with podgy	Back-off all nuts half a turn in sequence and then a full turn, catch any drops of product from flange in suitable container, remove every second fastener and finally all fasteners but last one. Spring flanges with podgy	Cover fasteners with anti-seize, back-off nuts half a turn in sequence and then a full turn, catch any drops of product from flange in suitable container, remove every second fastener and finally all fasteners but last one. Spring flanges with podgy		If flange does not spread easily review the situation and consider use of hydraulic spreader or wedges without damaging flange faces	

Task	Task Step Owner	Task Step Name (Max 3 – 4 words)	Task Description	Mat'1 – Tools and their Condition	Test for Correctness (Include diagrams and pictures)	Good	Better	Best	Reading / Result	Action if Out of Tolerance	Sign off
5		Clean flange faces	Remove old gasket and clean flange faces, remove any burrs, check face is flat with straight metal ruler and 0.05mm shim in gaps, no draw marks, pits or scratches allowed across flange face	25 mm wide metal scraper, 80 grit emery cloth	Flange face are totally clean and safely usable	Loose material removed, burr-free, flat face, no draw marks or pits deeper than 0.25mm	Grooves clean, flat face, no draw marks or pits	Bright, smooth, flat face, no groove damage or pitting, as good as new		Replace or machine flange with identical rating and grade if pits are deep, or are in close clusters, or not flat (pictures would be necessary)	
6		Pipe alignment	Check unrestrained pipe alignment	5/8" ring spanner x 2, or socket and ring spanner	Measure misalignment with vernier callipers on flanges with studs removed 	Flanges are unbolted and are in-line to within 2 mm	Flanges unbolted and are in-line to within 1.5 mm	Flanges unbolted and are in-line to within 1 mm		Cut pipe and remount flange to bring unrestrained flanges to within 1 mm alignment and 0.5 mm squareness to applicable procedure for the pipe material and grade	
7	Tradesman	Bolt hole alignment	5/8" ring spanner x 2	Check bolt hole alignment	Measure with vernier callipers on flanges with studs removed 	Flanges unbolted and holes in-line to within 2 mm	Flanges unbolted and holes in-line to within 1 mm	Flanges unbolted and holes in-line to within 0.5 mm		Cut pipe and realign flange to bring hole alignment of unrestrained flanges to within 0.5 mm	
8		Install new gasket and fasteners	Mount gasket and insert fasteners. Pre-cut studs to length and de-burr so that two full threads protrude out of each nut when fully tightened. Lightly lubricate the studs and the face of the nuts in contact with the flange.	Approved NEW gasket, NEW studs and nuts, bolt lubricant, podgy bar	Only new gasket and new fastener components used	Gasket slid between flanges and centred without damage and studs/nuts tightly and new studs/nuts fitted by hand	Gasket slid between flanges without and centred damage and studs/nuts lightly, pre-lubricated and fitted by hand within 2 minutes	Gasket slid between flanges and centred studs/nuts tightly, pre-lubricated and fitted by hand within 1 minute			
9		Bring flanges together	Pull-up fasteners snug tight in cross tightening sequence. Sung means flanges are in firm contact under about 20% of final bolt torque. It is obtained by the full effort of a well-built man pulling on a ring spanner until it can no longer be moved by hand. It can also be achieved by use of an impact wrench. When the spinning nut turns to blows, count	5/8" ring spanner or socket, feeler gauges	Flanges come together square with stress-free alignment	Wind nuts onto studs by hand so studs extend equal distance either side of flange. Tighten nuts finger tight and check that flanges are parallel to an accuracy of 0.4mm with the	Wind nuts onto studs by hand so studs extend equal distance either side of flange. Tighten nuts finger tight and check that flanges are parallel to an accuracy of 0.2mm with the	Wind nuts onto studs by hand so studs extend equal distance either side of flange. Tighten nuts finger tight and check that flanges are parallel to an accuracy of 0.1mm with the feeler gauges. Number the		If flanges are not parallel, directly 180° degrees opposite widest part of indicated gap, loosen nuts off one or more turns. Return to segment with gap and tighten until both flanges are in contact with gasket. This is necessary to prevent	

Task	Task Step Owner	Task Step Name (Max 3 – 4 words)	Task Description	Mat'1 – Tools and their Condition	Test for Correctness (Include diagrams and pictures)	Tolerance Bands			Reading / Result	Action if Out of Tolerance	Sign off
						Good	Better	Best			
			three blows, and the bolt will be snug tight <sup>68</sup> .			feeler gauges. Pull all nuts on both flanges up snug tight in correct sequence.	feeler gauges. Pull all nuts on both flanges up snug tight in correct sequence within 5 minutes	studs in the sequence of tightening. Pull all nuts on both flanges up snug tight in correct sequence within 4 minute		flange levering over the fulcrum formed by the outer edge of the two raised faces at points in contact with gasket. The restriction will cause exceptionally high flange to gasket clamp loading at this point, with possible damage to gasket, PLUS diverting necessary clamp loading bolt torque energy to correcting alignment on the opposite segment.	
10		Match mark fasteners	Match-mark nut position on <b>one flange only</b> with a pencil when all nuts on both flanges are snug.	Pencil	Scribed marks in correct position and easily observable	Match-mark the nut and flange	Clearly match mark the nut and flange within 1 minute	Clearly match-mark the nut and flange within 45 seconds			
11		Tighten fasteners	Turn each nut on <b>one flange only</b> an extra 1/3 of a turn to final position in cross tightening sequence. Re-tension continuously until all nuts are equally tight. No rotation of stud is permitted while tightening the nut.	5/8" ring spanner or socket. Impact wrench	Fasteners correctly tensioned to required nut position in right tightening sequence	Tighten nuts 1/4 of a turn in cross sequence and finally tighten nuts to 1/3 of a turn in cross sequence.	Tighten nuts 1/4 of a turn in cross sequence and finally tighten nuts to 1/3 of a turn in cross sequence in 5 minutes.	Tighten nuts 1/4 of a turn in cross sequence and finally tighten nuts to 1/3 of a turn in cross sequence in 4 minutes.		If a stud starts to rotate as the nut is tightened it indicates that the nuts were not snug to start with. Immediately stop and undo all studs and repeat nut snug tensioning procedure	
12		Test for leaks	Test flange for leakage at operating pressure, release pressure and retighten nuts on same flange as originally tightened								
13		Clean and hand back	Safely clean-up, hand-back, complete job record and sign-off and record Work Order history								

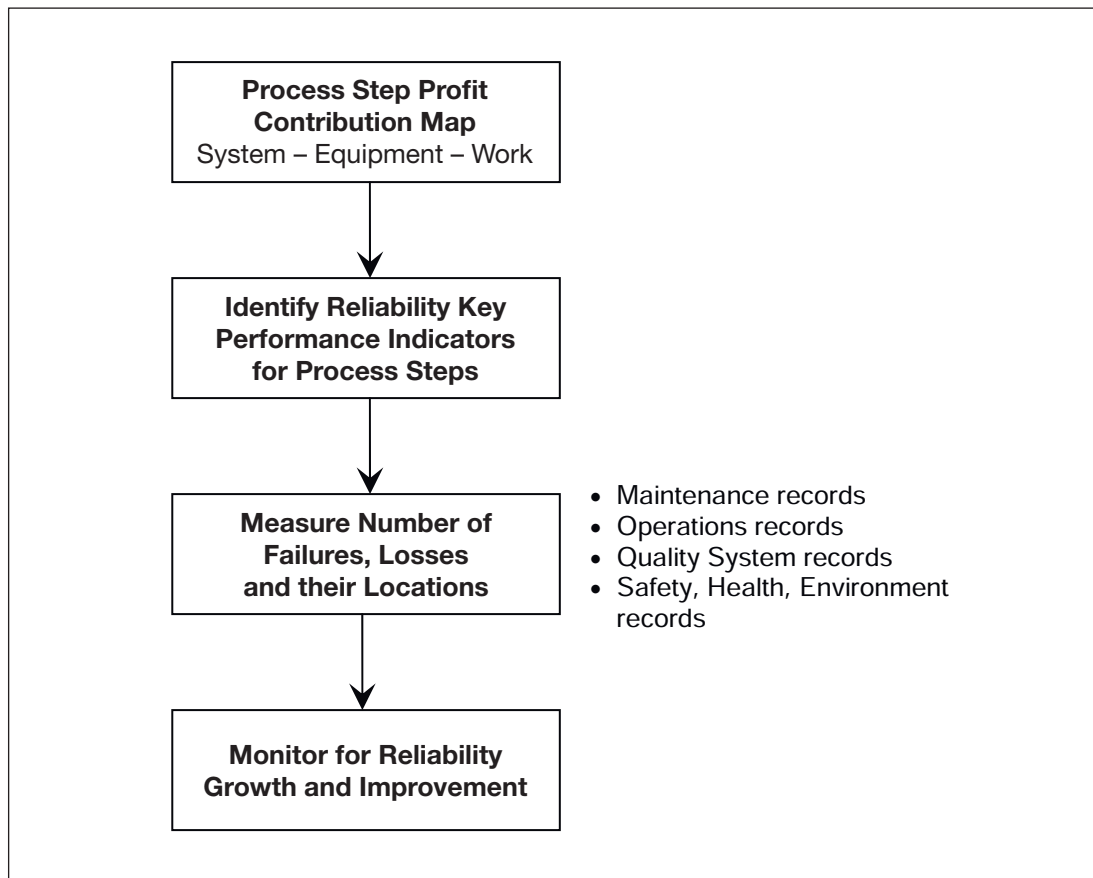
Figure 14.12 – Process Flow Map of Flange Connection Procedure.

**NOTE:** The example covers the method to use to create a 3 T procedure and is not the actual procedure to use when bolting-up flanges. Each organisation must research, develop and approve their safe practices and procedures for bolting flanges. The use of turn-of-nut on pressure flanges may not comply with the applicable pressure piping design codes.

<sup>68</sup> Sheppard, Alan T., 'High Strength Bolting', The DuRoss Group, Inc.



# PROCESS 5 – Operating Risk Monitoring and Measuring



## **Description of Process 5 – Operating Risk Monitoring and Measuring**

Good maintenance is a foundation requirement for good production, that is why Total Productive Maintenance had to be developed before Just in Time production could work for Toyota of Japan. It means that world-class maintenance is a foundation requirement for world-class production. They are supportive partners. Maintenance provides plant and equipment able to run at design duty, ensures machines are fit to make 100% quality product, and keeps equipment safe so it does no harm. To measure the business success of maintenance it is necessary to measure the profit it makes through the savings it contributes.

### **Process Step Profit Contribution Map**

Process maps are used to identify how to make a process more efficient. At each process step inputs are added and outputs are produced. Process Step Contribution Mapping lets you calculate the financial value added in a step. With detailed knowledge of step contributions and losses it becomes clear what to do to improve efficiency and effectiveness.

### **Key Performance Indicators**

Key Performance Indicators are required at the process step level and for the whole process. Those at the step level are used by the people doing the work to spot loss and waste. Those at the process level are for the people responsible for the operation to optimise the process and maximise profit.

### **Measure Failures and Losses**

Measure production downtime and process step wastes/losses to ensure that the maintenance and production efforts reduce them. Successful maintenance prevents equipment failures and minimises production losses. It does that by keeping plant and equipment fit and in good health. Well plant and equipment costs less to operate while making quality production to schedule.

### **Monitor for Reliability Growth and Improvement**

The results of improvement efforts need to lead to improvement. Show people how things are performing with visual diagrams, charts and graphs. When the performance is not what is wanted, team-up with people and plan what to do about it, then action the plan to test if the ideas solve the problems.

Use Key Performance Indicators to track the direction and progress made. Correct and improve those activities not yet performing well enough with the help of the people doing them by using the 'Change To Win' improvement program accompanying this book.

## 15. Process Step Profit Contribution Mapping

Plant and Equipment Wellness is as much about the wise use of money as it is about the wise use of engineering, maintenance and operational management to deliver top performance from production equipment and processes. Maintenance provides equipment reliability and reduces operational risk. It can also cut production costs if targeted on reducing production wastes by ensuring equipment and operating plant work efficiently. The higher you keep the process efficiency, the smaller are your losses, and the more profit you make. You need to know the size and location of your losses in order to target maintenance on improving the plant and process efficiency.

Process Step Contribution is a financial diagnostic tool used to produce key performance indicators of process efficiency. It provides a snapshot of the money flows in and out of a process step. With it you know where the wastes and losses are in your process. It is a fundamental tool for rapidly improving business profitability. Instead of waiting for financial reports delivered weeks after doing the work, Process Step Contribution maps the true costs of operating a process while it is happening. It provides accounting and cost data about each step in a process and allows identification of opportunities to improve the step's efficiency and effectiveness. Once each step's money flows are known it becomes clear where there are excesses and waste. Knowing the money made and lost permits focused and targeted process improvement and re-engineering to minimise wastes and losses.

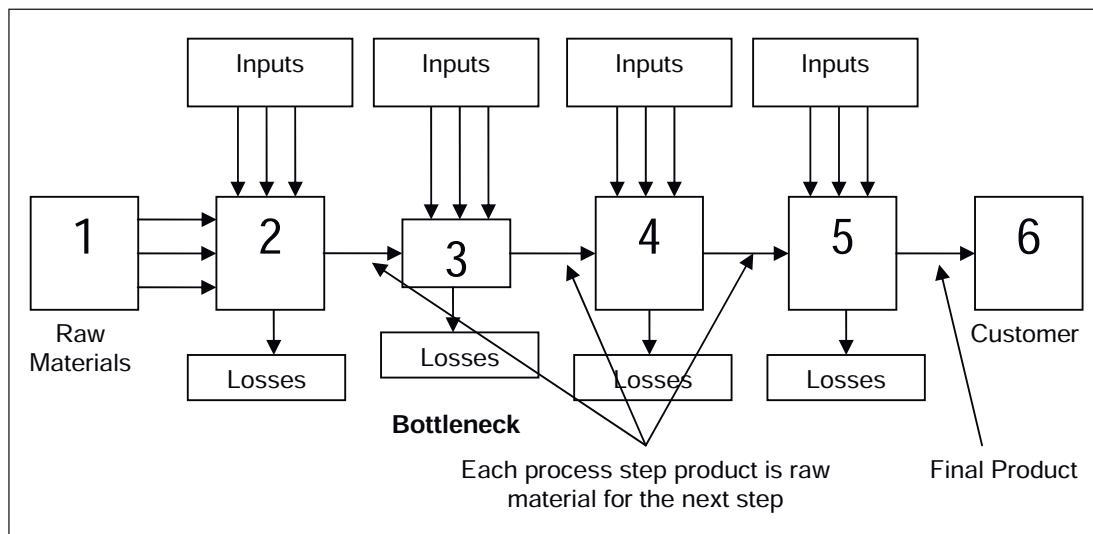


Figure 15.1 – A Business Conversion Process.

Process Step Contribution Mapping derives from the Toyota Production System value stream mapping. Whereas value stream mapping focuses on identifying the seven wastes in a process<sup>69</sup>, Process Step Contribution Mapping focuses on the financial gains and losses happening in every process step. The power of Process Step Contribution Mapping is its ability to identify exactly where every dollar goes in a business. Organisations examine the financial performance of their departments, but few businesses establish financial data collection on what actually happens within their processes. Preferring instead to employ supervisors and managers to control and direct the operation and get delayed results on actual performance.

<sup>69</sup> Liker, Jeffery K., 'The Toyota Way 14 Management Principles from the World's Greatest Manufacturer', McGraw Hill, 2004.



Application of Process Step Contribution Mapping employs cost accounting and activity based costing practices to accurately identify money movements throughout the steps of a process. The money movements in each process step are modelled using basic accountancy equations. Once the equations for each process step are developed, Process Step Contribution Mapping uses the financial information and data already available in the business to snapshot what is happening. The cost equations reflect the money flows in a step and their development requires engineering precision to capture every cost and waste. By understanding the money flows in a process step it becomes possible to identify improvements and better practices to optimise that step, and so make the whole process more productive and profitable.

Figure 15.1 is a symbolic production, manufacturing or service process showing a series of numbered boxes for each conversion step. The materials, utilities, services and labour flows are represented by arrows.

Production, processing and manufacturing systems turn raw materials into finished products through a series of steps that progressively convert them into saleable products. Typically, a conversion process takes raw materials and adds inputs such as labour, utilities, (like power and water), specialist services, (like engineering and maintenance), supplementary materials, (like boxes for packaging) along with other necessary requirements to make products customers buy. Maximising profit requires both efficiency and effectiveness from every step.

An effective process makes and delivers what the customer wants. An efficient process delivers the profit the shareholders want. An important job for managers, economists, accountants and engineers is to develop business systems that reliably achieve seamless operation to the benefit of the organisation, its customers and community. This requires on-going commitment to continually improve and tune the organisation to be more efficient and work faster, better and cheaper.

### **Properties of Production Processes**

In Figure 15.1 raw materials and added inputs enter each step. The process steps use these to add value and make the products produced by the organisation. During production the product increases in value equal to the sum of value added in each conversion step. Each value-adding step contributes part of the profit. A process step does not produce perfect conversion and some losses occur. The customer pays for those unwanted losses when they buy the product.

A production process should only make what the market will purchase. Otherwise it ties-up money in inventory that no one wants. Balanced production means buying raw material and inputs at the same rate that you sell the product. The market and business economics regulate and control the production rate and the amount of raw materials and inputs you buy. This is the essence of a market-based, capitalist economy – products made, that people want, in production systems balanced to the demand.

From Figure 15.1 we can state a few simple properties of a business process:

- i. A process step adds value if the output is worth more than the sum of raw materials, inputs and losses.
- ii. The customer demand rate dictates the ideal manufacturing rate.
- iii. The process design establishes production efficiency and costs.
- iv. Process design determines product quality.
- v. The bottleneck limits the maximum throughput rate for the process.

## Bottomless Pits of Losses and Waste

Process losses behave differently to anything else in the production process. Market demand does not naturally limit them. Their only limit is how much money is available to be lost in the production system. All wastes take money from what would have been profits. Because there are no systematic internal constraints on waste they are controlled by minimising them during design and by managing them to minimal levels during operation.

Usually the wastes are not seriously considered in business process design. Standard accounting and cost accounting systems do not measure them. The wastes include the obvious waste product and scrap materials commonly associated with production waste. But there are many other types of waste produced. Other wastes which are numerous and common, but not often noticed, include such things as excess movement, lost heat, lost water, lost energy, excess storage space, excess in-process inventory, excess time, lost time, quality defects, excess forklift pallet hire, excess equipment hire, safety incidents, environmental incidents, excess paperwork, excess manning, and many, many more. Figure 15.2 is a business losing profit through its wastes.

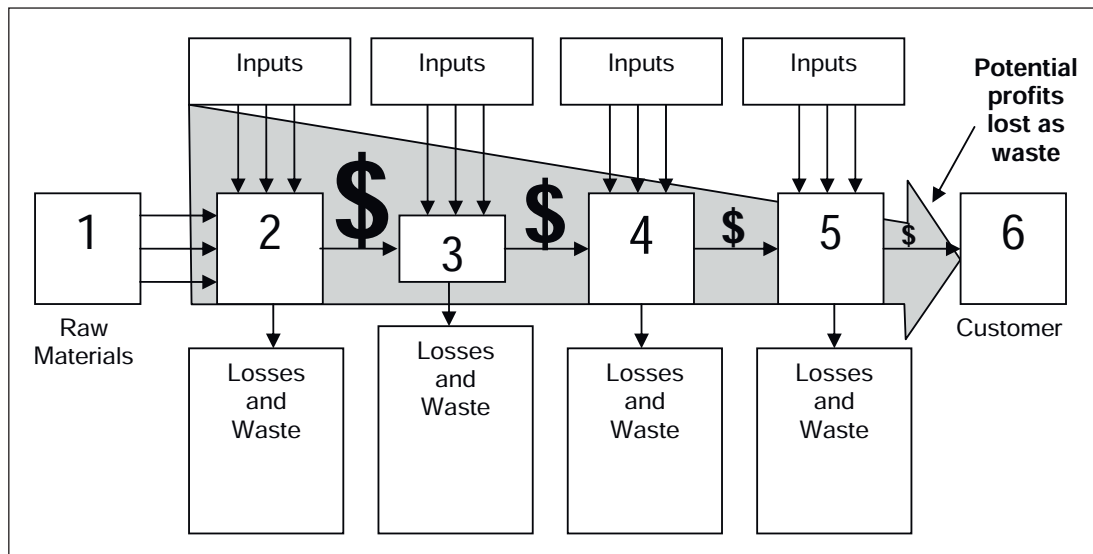


Figure 15.2 – Losses and Wastes in a Production Process.

Some of these wastes are identifiable by using value stream mapping, typically time, motion and distance, but the technique does not price lost moneys. In order to recognise the cost impact of waste it is necessary to identify their real financial loss to a business with Process Step Contribution Mapping. Waste creation has no natural means of self-control beyond bankrupting the business. Businesses need control systems that monitor the waste and force its minimisation and eventual total elimination. There are now two additional properties of a process that we can state:

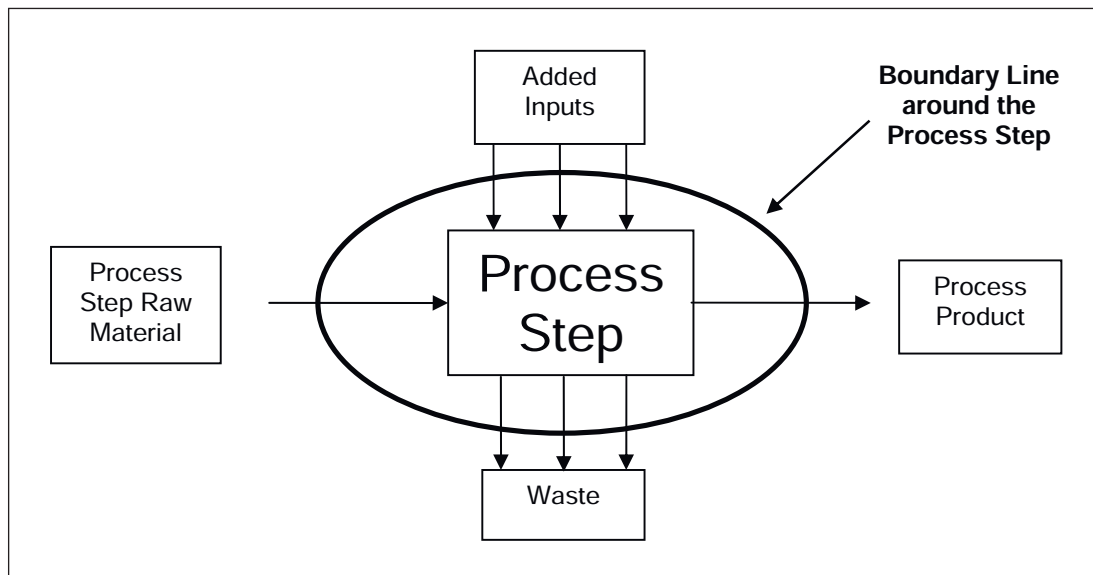
- vi. Wastes extract effort and profits from a process.
- vii. A process can turn raw materials and inputs into waste so that the process makes waste instead of profit, to the point where waste consumes all the profits.

We can use these seven properties of a business process to understand how money behaves within it and identify the costs and wastes that reduce its performance and profit. This is Process Step Contribution Mapping. It spots all wastes and identifies all moneys lost.

### Identifying Value Contribution

Once a process is operating concerns naturally turn to making the product on-time. The demand to make product on-time often overrides the need to make it cost effectively. This leads to situations where everyone is busy making product, but no one is busy making profit. If this situation occurs in an organisation the creation of waste, instead of profit, dramatically rises. Process Step Contribution Mapping helps manager, supervisors and engineers collect the cost information needed to operate a production system efficiently and effectively.

Each process step has its own raw materials fed from the prior process step. It has its own added inputs needed to make the conversion. From each step come a 'product' and the wastes. Each process step is clearly identifiable from its predecessor and its successor and is self-contained in performing its conversion. Each process step is independent of the others and is a whole system in itself. This allows us to analyse each process step separately. To make clear which process step is being reviewed draw a boundary around it on the process flow map. An example of segregating a process step for analysis is Figure 15.3.



*Figure 15.3 – Local Process Step Analysis.*

To determine process effectiveness and efficiency we need a measure. A good measure to use in business is money. Money is the universal language of commerce and most people understand the concept of using money to value an item or service. By using money to measure a process step's raw materials, added input's cost, cost of wastes and the process step product, we can trend the step's profit contribution while making the product.

Figure 15.4 indicates the various money flows in and out of a production process. By analysing the costs of the raw materials, the costs of the additional inputs and the wastes lost from it, the contribution of a step to the final product cost can be determined. Monitoring the costs and value contributions of each step provides a means to measure the efficiency of its conversion processes. The more value contributed in a process step the more financially efficient is the step. By knowing the cost of all inputs and all wastes, you can identify the steps having the greatest effects on operating profit. With each step's contribution information, managers, accountants and engineers can focus on new cost reduction, productivity and process improvements that return the best value.

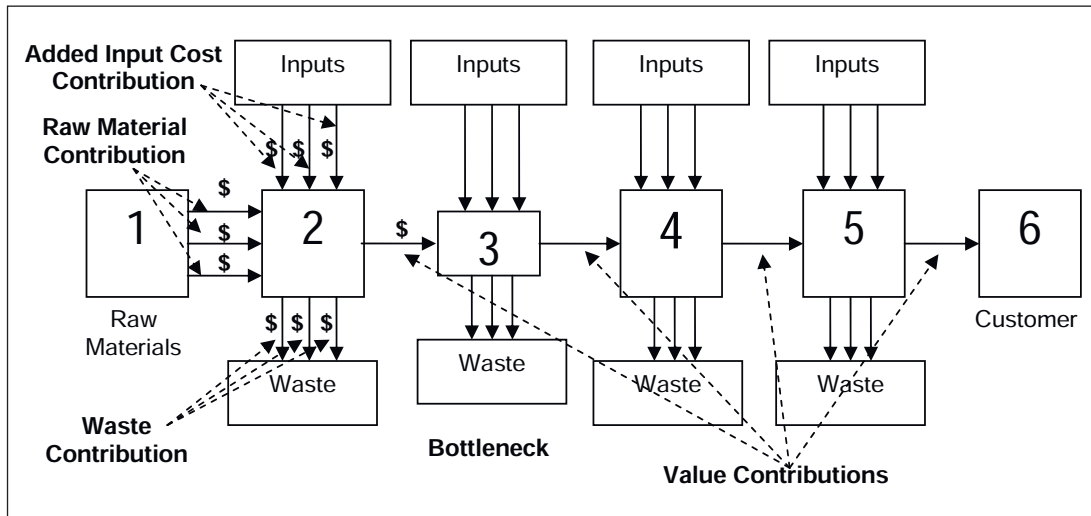


Figure 15.4 – Production Process Money Flows.

Figure 15.5 indicates how to identify each money flow associated with a process step. The boundary line makes it clear there is money entering from 'raw materials' and the added inputs required in making the process conversion. Each process step delivers its own process 'product' with its value contribution from the value-adding performed in the step. In addition, there are lost moneys that reflect process and operating inefficiencies, wastes and losses.

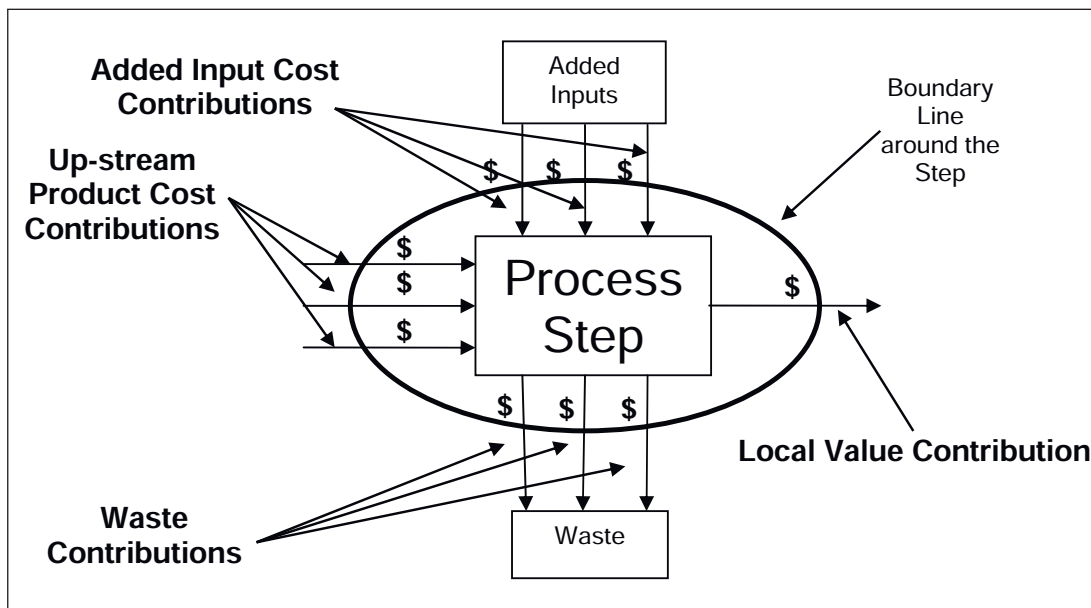


Figure 15.5 – Local Process Step Money Flows.

By identifying a business as a process of interconnected steps, it becomes possible to focus on the financial performance of each step and optimise it. Process Step Contribution Mapping manages operating performance hour by hour by monitoring the costs into and the value out of each process step. Once a step's in and out money flows are identified they are used to analyse its profitability. The necessary equation is:

$$\text{Raw Material Cost} + \text{Added Inputs Cost} = \text{Value Contribution} + \text{Waste} \quad \text{Eq. 15.1}$$

The value contribution is found from equation:

$$\text{Raw Material Cost} + \text{Added Inputs Cost} - \text{Waste} = \text{Value Contribution} \quad \text{Eq. 15.2}$$

Strangely, from equations 15.1 and 15.2, it seems we pay for waste twice, once when we buy it as an input and second when we throw it away as lost value.

### The Process Step Contribution Map

To identify money flows it is best to start by drawing a cost map showing the money movements occurring in the entire process. A simple Process Step Contribution Map is shown in Figure 15.6 for a section of a beverage canning line. Costs cascade into a step and wastes from the step.

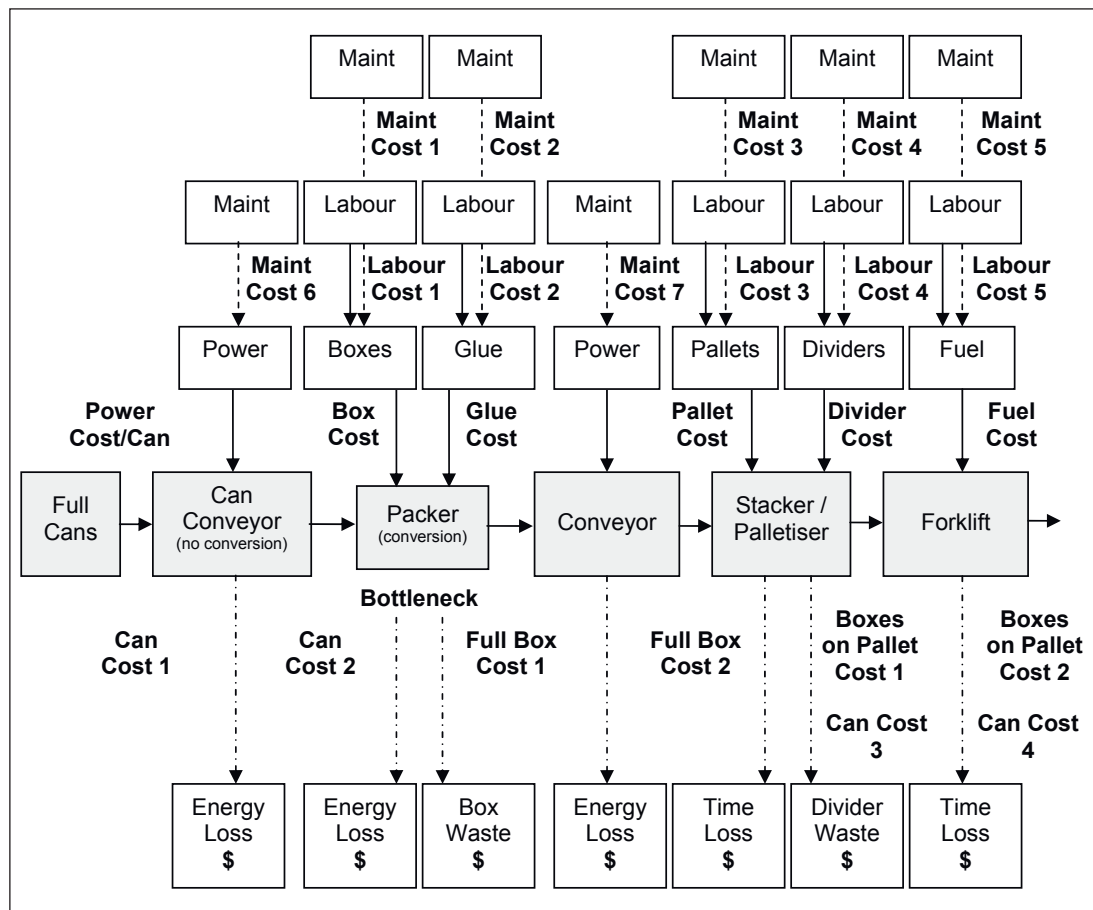


Figure 15.6 – Process Step Contribution Map for a Canning Line.

### Cost Analysis

The power of Process Step Contribution Mapping is the clear financial understanding provided of the real value produced in each production step. By displaying where the money goes into, around and out of a process, the cause of costs and profits becomes clear to people.

It is important every dollar spent in the production of goods is accounted for on the process-step contribution map. It is necessary to capture every cost, from the smallest to the largest,

as it is spent. Activity Based Costing (ABC) is the most appropriate accounting technique to apply when determining process step costs. Standard costing is not suitable since overheads are allocated as a proportion of total direct costs of a process and not by individual process step. It may be necessary to do time and motion studies in the workplace to identify all time and resources used in a step. ABC is used to identify every cost with its component costs, and even sub-component costs.

The reporting frequency for a process step depends on the step cycle time (how long it takes work to be processed through the step) and how long it takes to measure all money flows for the process step. The appropriate period used to measure the mapped costs should be as short as possible to give feedback quickly enough to match the volatility and importance of a situation. With the progress of computerisation, electronic tracking of material and automation of cost information, it is possible to give value contribution information to every operator in a business. Process Step Contribution Mapping lets shop floor people see how their process behaves so they can adjust their behaviours and decisions accordingly.

Real-time cost collection is ideal, but that requires using computerised on-line recording of all inputs, outputs and wastes, along with the software to process the data and display it. Reporting during and at the end of a processing cycle is useful for adjusting process efficiency. In some cases, it might be necessary to map a particular process step more often than the entire process because of its importance in the operation. The process step contribution map ought to be updated for each shift so people can identify opportunities to improve every day. When Process Contribution Maps are generated weekly or monthly they become historical indicators for reviewing process effectiveness.

### **Developing Profit Contribution Equations**

The money movements on the cost map represent the materials, labour, wastes and the value-added for each step. They can be represented by an equation of the type shown in Equations 15.1 and 15.2. The cost of producing product through the whole process is simply the amalgamation of the individual steps. A financial model with such engineering precision permits the monitoring of the real cost of production and allows determination of how profitable it is to do a job. It identifies where there are costs and wastes to remove to get the maximum operating profit. Because most businesses cannot measure their process wastes it often needs perseverance and creativity to gather the data and to develop the equations. Once a process and its steps are mathematically detailed it is a simple matter to conduct 'what-if' sensitivity analysis to identify the critical success factors affecting its optimisation. It then becomes clear where the process needs to be changed to maximise performance and profitability.

Where detailed monitoring of all process step money flows is not available, an approximating cost model is developed. The approximating equation is based on the costs related to a unit of production. Example E15.1 shows how Profit Contribution approximating equations are developed for the manufacture of concrete reinforcing steel in an operation that could not introduce process step money flow monitoring.

### **Collecting Cost Data**

A production process generates the cost data needed for analysis and management as it makes the product. The cost of materials, labour, utilities, overheads and services are on invoices or payslips. Not normally available are the process costs accurately allocated to the process steps that incurred them. To manage a process step's efficiency it is necessary to cost every input, product and waste accurately. An approach used to identify the money flows in a process

step is to use the process step job procedures and work through them identifying the process step raw materials and inputs added, the wastes produced and the product made. As shown in Figure 15.3, put a boundary around the step to clarify the associated 'flows'. Many of the inputs, wastes and products are on the process design drawings, or found in engineering documents, equipment manuals and standard operating procedures. Confirm the data by personally observing every step for a full cycle of production.

Onsite identify all electrical power supplies to the equipment, all pipes supplying services, all process products into the step, all added inputs, all outputs and wastes from the step. This includes measuring all manpower and overhead persons' (such as management, supervision, information technology specialists, etc) efforts, times and costs incurred by the process step. It incorporates measuring forklift movements, vehicle movements, personnel movements, etc. that occurs in the period observed. It includes counting the number of lights and time they are on, how often equipment is hosed-down and the amount of water used. Collate and cost all activities in a spreadsheet. It will be necessary to go as far as identifying minor costs, like rags used for cleaning equipment, the cleaning detergents used, any personal safety equipment and company brought clothing each operator requires during the period, etc. Over a year, these minor expenses can grow into serious costs that are easily wasted. Find every dollar that goes into a process step and that comes out of it. Put on the mantle of the crime investigator and look for all the clues to the puzzle. Unearth the truth of where the money goes in each step.

When studying a process step that involves movement of product and/or people, for example storing materials in a warehouse, time the length of the move, measure the distance moved and identify the equipment used in the work. Put a cost to the movement of product and materials to test if it delivers real value for the expenditure.

Because the Process Contribution Mapping process needs to identify every cost individually, it is preferred that all overheads be identified separately as they are used in each process step. By allocating overhead costs proportionate to direct labour, an inaccurate mapping of the true costs result because overheads are not really expended in proportion to labour hours. But if it is not possible to allocate overhead costs separately, they can be allocated in proportion to their identified usage in each process step. The accuracy and completeness with which the process step costs are collected will directly determine the effectiveness of the step contribution map as a management control tool. If data is complete and true, then it is believable and useful for decision making.

All costs are in business systems such as payroll, inventory and accounting. Unfortunately, they most likely will be totalised costs. The labour will be for a person's total time at work and you need what they spent in each process step. The power bill will likely be for the whole of a building, whereas you require the cost of lights and power for each machine in that building. The purchase of safety gloves will be in batches of dozens at a time but it is necessary to know how many the people working in a process step used.

The most accurate approach is to get the real usage of inputs and wastes. For example, the power used by the lights and machinery in the process steps need to be collected for the period concerned. If that is not possible it becomes necessary to proportion the machine's share of the building's power based on the electric wattage used in the process step. But by proportioning you introduce inaccuracies that may cause people to question the conclusions. If necessary, introduce special means to capture cost information. Develop timesheets and record-of-use sheets, connect chart recorders to electrical equipment and install Doppler-effect meters to measure flows in pipes. If accurate cost control is important to the success of a business then spare no effort to discover the true wastes, costs and losses you suffer.



## Capturing Process Step Costs

The work involved in identifying and costing component inputs, products and wastes for each process step can be large. Use modern technology and computerisation as much as possible to capture as many of the costs automatically. Identify labour by using electronic time cards and time clocks. Electronic tagging or bar coding can be used to identify material movements. With Global Positioning Systems your equipment, materials and people movements are traceable.

If wastes cannot be identified electronically it becomes necessary to conduct site surveys to quantify them in order to develop a factor for use in calculations. It may be useful to change work procedures and include the recording of process step waste as standard practice. If waste is not regularly measured, conduct audits periodically to confirm the waste factor allowance and alter the Process Step Contribution Mapping equations as necessary.

Even if Profit Contribution Mapping is not adopted by your organisation, consider permanently introducing the counting and measuring of wastes to allow identification of the causes so you can address them before they get even worse.

## Labour

**Direct Labour** comes from the time sheets of the people employed directly in the process step being analysed. If the people work in another process step, then only cost time expended in the process step under investigation. The direct labour cost is the pay rate, including on-costs, paid to the people working in the process step, multiplied by the time they spend in the process step during the period costed. Their on-costs include allowances, superannuation, benefits, etc, proportioned to the period. Do not include allowance for overheads, as they are separately costed.

**Indirect labour** costs are the time spent by persons, other than the directly involved people, to complete the process step. It is necessary to measure and allocate times for indirect labour. This includes maintenance, supervision, middle and senior management time, inventory and storage personnel, purchasing department personnel, quality control personnel, etc. Identify these costs by interviewing relevant people to find out the time spent on various process steps. During a site inspection watch the process for a full production cycle and observe who interacts with the process step.

The indirect labour cost is the pay rate paid to the indirect people, including their on-costs, multiplied by the time they spend in the process step during the selected period. On-costs include allowances, superannuation, benefits, etc, proportioned to the period. If indirect labour is missed over a short period, a proportion of all the missed indirect labour costs still need to be allocated to the period. Take a longer time and collect all the indirect labour costs for the longer period. Then proportion and allocate them for the period being reviewed.

**Indirect expenses** are those costs incurred due to the presence of the 'indirect' people in the operation. An example is a manager's car and fuel paid out of operating revenue. Allocate them in proportion to the hours spent in the process step by the expense owner.

## Subcontractors

Allocate subcontract labour and materials the same as employed direct labour. There will be an invoice for the subcontractor's time and materials, and from it is extracted the allocation of times and materials for the work done in a process step.

### Utility Services

Measure electricity, water, gases and such services and allocate to the process step usage during the period.

### Management, Engineering, Administration, Supervisory Costs

These costs cover the time managers, engineers, supervisors and administrative support staff spend doing work related to requirements of the process step. For example daily meetings, site inspections, human resources requirements, problem solving process issues, invoice matching, stores management, maintenance planning, etc. All support persons who interact with the process step need their times and costs recorded against the step. People can be interviewed and asked to estimate the time they spent on a process step. If necessary have them keep time sheets to record the actual times involved with the process during the period.

### Added Input Materials

**Direct material** costs are for added input materials actually used in the process step. They are the obvious additions of substances into the process step. This includes such things as electricity for motors, boxes for packaging, lubricant for equipment gearboxes, air for pneumatic rams, etc. Typically, these materials enter the process step in a physical form. These costs depend on the quantity and value of each input material used. It requires counting the amount of the material used and multiplying by the unit cost of the added material. Identify material costs from invoices for the material. Sometimes the added material is from within the organisation and no invoices are available. In such cases it will be necessary to get an accurate cost for the added material from the process used to make it. If none is available calculate it from the cost of the labour, ingredients, handling and manufacturing charges, etc, used to make it.

**Indirect material** costs are the costs associated with the indirect functions required to perform the process step. Such as paper for recordkeeping, electricity for office lighting, a maintenance planner's computer, the cost of forklift hire to move pallets, the building storage space for spare equipment parts, etc. All these costs are real costs incurred to conduct business that supports the production processes. It is necessary to measure them and quantify them so that they have a value. Measurement can be by stopwatch, distance, counters, etc. Identify the proportion used in the step and the amount wasted.

### Raw Material/Up-stream Product Costs

Determine the cost of the raw materials and/or up-stream products entering a process step. An accurate value may be available from the accounting, or production department. If it is not available accurately it will need calculation for each prior process step from the start of the process.

### Identifying and Costing Wastes

**Direct waste** is any direct labour or direct materials added into the process not fully used-up in making a product. Where an added input gradually converts through a number of process steps, it is not wasted if it is fully used. Unconverted added-input is waste. For example, in some chemical processes the chemical reaction absorbs only a portion of the mixed ingredients. Those ingredients not converted by the reaction are wasted. A laboratory analysis can identify unconverted ingredients and tell how much was unused. Another example is water used to clean equipment. It does not go into the product but disappears out of the process and is a waste. Leakage from the process is waste. Spillage from a process is waste even if it is picked-

up and returned to the process. Another example of waste is side-steam materials collected in bags or bins and disposed of as rubbish.

**Indirect wastes** are those wastes related to the unnecessary use of indirect labour and indirect materials. They are more difficult to identify because they are not easily observable. Examples include wastes related to lost time in meetings, to lost energy, to lost compressed air, to safety equipment thrown away before fully used, and storing unneeded materials in a storeroom. There are numerous instances of such wastes. The detection of indirect wastes is through observation. Observe all process steps and their inputs to identify wasted costs, materials and product. Look in the rubbish bins used in the process step area and see what people throw out. Include the lights and air conditioning left on overnight unnecessarily. Develop and instigate systematic means to spot and record the waste and its value during the period investigated.

### Comparison with Standard Costs

Every organisation should have a standard costing system for its products. If standard costs are available, use them as a parallel double-check and compare them with the costs from the process step mapping analysis. Investigate variations of more than 10% from the current standard costs because the variation shows that there is a pricing problem.

### Performance Measures and Reporting

Problems highlighted by profit contribution analysis require Management and personnel to use new strategies to maximise the value from their processes. After a process step is analysed in detail it is easy to understand and appreciate how its many factors interact and impact each other. The accurate costing of inputs, wastes and conversions will identify efficiency problems. Through detailed questioning and root cause investigation, the reasons can be uncovered and then the required changes can be made. If change is required it is necessary to determine what that change will be. Issues will need discussion with everyone concerned in order to fully appreciate and understand their history. The new changes will also need discussion, review and analysis for possible unwanted consequences. New changes introduced will require their own measurement, monitoring and reporting.

Selecting the right measures to monitor and report will be critical to the success of the change process and to the speed of its implementation. The measures need to be meaningful to the users, truly reflect the situation, be within the user's control to improve, and inspire continued improvement. One of the change strategies will be to introduce performance measures that identify poor efficiencies and the practices that cause them.

Performance measures based on the issues identified by the analysis are intended to drive the right behaviours and actions. Use process control charts, graphs and trends of the measures to show performance improvement. Some typical indicators to use are listed below. Measures must suit specific circumstances. The purpose of measuring is to know exactly what is happening. After understanding the current situation an assessment is made as to whether it is satisfactory, or it needs to be changed. The effects of a change will appear in the performance measures. It may take as long as several weeks or months to observe the effects of a change. Where the measures indicate an unsatisfactory result a correction is necessary to get back on-track.

**Usage Efficiency:** This is the classic output divided by input. Select the important process flows. Develop appropriate efficiency measures for each, and trend them over time.

**Productivity:** These are measures of process performance. They are time based ratios of output during the period. From the contribution map select the productivities that are important to measure. Measure Productivity at both the process step level and the global process level.

**Throughput:** This measure is a count of what passes a selected point in the production process during a period.

**Waste Cost:** This measure counts the cost of waste in dollars per dollar spent to purchase the original material.

**Quality:** Is the proportion of production that meets customer specification. It is another measure of a wasteful process.

To get a complete understanding of what happens in a process requires more than one measure. Business processes involve many interactions and may have several variables that affect each other. It may take a number of ratios to identify what is occurring, though you do not want to use more measures than necessary. Maintaining measures requires time and money, which are then not available for use elsewhere. Experiment with the right measures to apply before deciding which to use. Keep performance reporting simple by using headings to categorise reports and visual means for displaying information. Show trends graphically in a form that makes their message clear. Use balloon notations in graphs to highlight issues that need attention. Apply colour and font variations to enliven the report. In tables show summary entries and totals for each category. Keep the details for when people ask. Draw people's attention to the conclusions and their implications by providing an executive summary at the start of the report.

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### **Example E15.1: Process Cost Mapping**

#### **Approximating Cost Equation for a Manufacturing Process**

The organisation produces bent and straight reinforcing steel bar used in building construction by uncoiling rolls of different size bar through a machine, which then bends the bar to the required shape and cuts it off the coil. The cost map for the production is in Figure 15.7. The cost map shows the manufacturing process with each machine. It breaks the manufacturing process into its separate steps to show where costs arise during production. The manufacturing process runs horizontally across the page and the costs incurred at each step run vertically into the process at the step. The cost map identifies every input cost and waste for each step. Realise that every input to a step is itself the result of another process, which the contribution method can also analyse.

By laying-out the process in a flow diagram it becomes clear which steps incur costs and from where costs arise. To have a cost equation that correctly represents the money flows we must have all input costs and all outputs for each step. If the actual costs incurred at each step are not available it is necessary to develop cost estimates from accurate historical data, or by observing the step and recording inputs, outputs and wastes.

Difficulty arises when there is no real data available for individual inputs and none can be collect on-site. In such cases it becomes necessary to allocate costs using standard cost methods and hope they closely reflect the real situation. Figure 15.8 is a simplified version of the cost map in Figure 15.7 where costs are allocated and proportioned for each individual step as advised by the operations management and accounting people in the business. This example describes a means to estimate the cost of producing a piece of work through the production process shown in Figure 15.8. The requirement is to represent the production process by a cost equation so that estimates of the cost of work can be made in order to determine if it is profitable to do a job and to identify where costs can be saved in producing the item. Each work piece from the cutting and bending machine consists of lengths of bar either made straight or made with bends and straight lengths between bends. The cost of a

work piece depends on its diameter, the length of material used, the number of operations and movements performed on it at each step, plus its share of unmeasurable business costs allocated to each step.

The variables for the steel bar production are:

- Bar diameter
- Work piece total length
- Number of bends in a work piece
- The bend complexity
- The total factory production time for the work piece

Once the cost to produce one unit of work is know, then the cost per production run can be estimated by multiplying the cost of a production unit by the number of units to be produced.

Taking each process step one-by-one from the start of the process, the cost map allows easy identification of component costs and wastes. Reflect each step in the form of calculation shown by Equation 15.2, and repeated below.

$$\text{Raw Material Cost} + \text{Added Inputs Cost} - \text{Waste} = \text{Value Contribution}$$

Applying the equation to the ‘Received in Factory’ step from Figure 15.8, its value contribution equation is:

*Cost of steel coil to make a unit of product + That step’s proportion of allocations for one unit of product = Step value contribution per unit processed*

For the ‘MACHINE – Coil / Uncoil / Straighten / Bend / Cut’ step its value equation is:

*Value carried from prior step + Labour for the step to make one unit of product + Power used in the step to make one unit of product + Maintenance on the machine caused by one unit of product + That step’s proportion of allocations for one unit of product – Scrap from one unit of product = Step value contribution per unit processed*

Perform this calculation for each step in the process with a computerised spreadsheet. The analysis identifies the value-added at each step, and the impact of its costs and wastes. If the unit of product is too small to get sensible unit costs then use the smallest multiple of units for which costs and allocations can be reliably and accurately determined.

Model the entire production line or process by adding together the equations for each process step.

## Developing the Cost Equations

The first step is to draw the complete process as a flow diagram showing each stage of production as a separate box on the flow diagram. Within each box briefly name the step with words that describe its function so it can be identified separately to other steps. On the flow diagram identify every input, output and waste for each step.

It is necessary to identify and separate the fixed costs and the variable costs for each step. Typically, fixed costs are a constant cost for the business and do not change with the work, whereas variable costs are dependent on the work piece and change as the type of work changes. The production cost consists of the fixed costs and variable costs added together. The basic form of the production cost equation is:

$$\text{Production Cost} = \text{Fixed Costs} + \text{Variable Costs}$$

To be able to use the equation for every item of work put through the process it is best to base the costs incurred in production on factors related to the work piece itself. Allocate costs related to variables that change with the type of work piece so that the estimated cost reflects work piece complexity. For example diameter, size, weight, complexity, etc. These variables in the case of the steel bars are:

- Bar diameter (available from the design drawings).
- Work piece total length (available from the design drawings).
- Number of bends in a work piece (available from the design drawings).
- The bend complexity (available from the design drawings).
- The total factory production time for the work piece (available from standard costs or a work and motion study is performed to determine typical production times).

For each process step in the cost map write the costs associated with its inputs and wastes. Separately describe the logic behind developing the cost equation so that there is a reference explaining the equations (see the descriptions at the end of the example).

Keep variable costs and fixed costs separate. The variable costs connect to factors related to the work piece, whereas the fixed costs are independent of the work piece. Collect costs into a summation equation of identical variables. Look for means to arrange and combine costs and simplify the equation where possible. In this way, work through each process step to develop its own equation. The total process is the sum of its individual steps.

The example cost equation below combines the individual process steps into an overall equation for the steel bar production process. The numbers in *italics* reference the description of the costs.

The cost for each work piece depending on its diameter consists of:

$$\begin{aligned} \text{Variable Cost / metre straight} &= \text{Cost of machine power to feed and straighten coil (2)} \\ &+ \text{Handling/bundling labour, including on-costs (3)} \\ &+ \text{Maintenance of coil holder, rollers, etc due to machine use (4)} \\ &+ \text{Steel cost per metre (12mm and 16mm) (1)} \\ &+ \text{Coil loading – crane and labour, including on-costs (8)} \\ &+ \text{Straightening rollers set-up labour, including on-costs (11)} \\ &+ \text{Scrap, including crane movements of bin (13)} \\ &+ \text{Finished tag storage – building amortisation \& maintenance (17)} \end{aligned}$$

$$\begin{aligned} \text{Variable Cost / bend} &= \text{Steel cost per bend (12mm and 16mm) (5)} \\ &+ \text{Cost of machine power to do a bend (6)} \\ &+ \text{Maintenance of machine due to use (7)} \\ &+ \text{Bends' set-up labour, including on-costs (12)} \end{aligned}$$

$$\begin{aligned} \text{Variable Cost / work piece} &= \text{Scheduling, including on-costs (9)} \\ &+ \text{Finished job moving – crane \& labour, including on-costs (14)} \\ &+ \text{Loading truck/trailer – crane \& labour, including on-costs (15)} \\ &+ \text{Despatch to customer – paperwork, invoicing (16)} \end{aligned}$$



Fixed Costs / production hr = Supervision – Leading Hand, Supervisor, including on-cost (19)

- + Invoice processing, including on-costs (18)
- + Production Planner, including on-costs (20)
- + Senior Management/Accounting costs and on-costs (21)
- + Hire of factory crane (22)
- + Maintenance – crane (23)
- + Maintenance – general costs and building (24)
- + Factory lighting (25)
- + Offices' running costs (Admin Office, Production, Despatch) (26)
- + Safety (27)
- + Quality Control (28)
- + Estimating and quoting, including on-costs (10)
- + Customer disputes and resolution, including on-costs (29)
- + Production Coordinator (30)

The cost equation for the complete process for a unit work piece becomes:

**Production Cost = Cost per m straight**

- + Cost per bend**
- + Cost per piece**
- + Cost per production hr**

Once the cost of one work piece is know, then the cost per job size can be estimated by multiplying the cost of a work piece by the number of work pieces required.

### **Derivation of Process Step Costs**

*(1) Steel cost per metre (12mm and 16mm)*

This is the cost of one metre of coil delivered into store. It includes:

- all steel mill cost
- all transport costs nationally and locally
- all off-loading forklift use and labour
- delivery documentation processing
- all stores receiving and inventory updating
- the cost of storing the coil on-site, such as rates, land tax, site maintenance, etc.

Both 12mm and 16mm coils go through the machine. The cost is required by metre length.

*(2) Cost of machine power to feed and straighten coil*

This is the power required to unroll the coil and run it through the straightening rollers. It will



vary for each size of bar. The cost is by metre length.

*(3) Handling/bundling labour including on-costs*

This is the labour cost to wait and grab a work piece, then lift, move to the stack and place it onto its bundle, including the time needed to tie the bundle for a lift to be despatched. The time taken depends on the size (length x width) of the work piece. The cost is by metre length.

*(4) Maintenance of coil holder, rollers, etc due to machine use*

This cost is from the wear and tear on running parts used to unroll the coil and run it through the straightening rollers. It can be estimated by metre length from the cost of replacement parts (coil holder and straightening rollers) plus the labour to change the parts divided by the total length of coils put through the machine in the time since replacing the last set of roller parts.

*(5) Steel cost per bend (12mm and 16mm)*

The cost of steel required for a bend. Both 12mm and 16mm bends go on the machine. For a 90° bend this is three-quarter the bar diameter. For an 180° bend it is one-and-a-half times the diameter.

*(6) Cost of machine power to do a bend*

This is the power required to put a bend in the steel. It will vary for each size of bar and amount of bend. The power is best determined by using a power meter mounted on the machine to measure the power used over a long period of time (at least a week). Alternately, make a rough estimate from the electric motor size and the length of time it is used.

*(7) Maintenance of bender due to machine use*

This is the maintenance cost of the bending head on the machine per bend. Calculate it by the maintenance costs over a period divided by the number of bends performed by the bender during that time. The number of bends in a period comes from historical records or by site observation.

*(8) Coil loading – crane & labour, including on-costs*

This is the cost to forklift the coil into the building, lift it by crane to its uncoiling cradle at the machine and return the crane. Labour cost is also included. Because a coil is of known length, calculate this cost by the metre.

*(9) Scheduling, including on-costs*

This is the cost to schedule a work piece. It includes the time spent reviewing the drawings, calculating measurements, entering information into the business systems and printing and handling paperwork, including the cost of stationery. From the scheduling process the bar schedules are developed. A cost per work piece can be determined from the cost of time spent per schedule, divided by the number of work pieces in a schedule.

*(10) Estimating and quoting, including on-costs*

This is an hourly cost allocation for the time and resources taken to estimate and quote a job, multiplied by the time taken to make a work piece. The bigger the job the longer the time taken to do these tasks. The cost can be determined from historical averages of time and resources required provide prices to customers.

*(11) Straightening rollers set-up labour, including on-costs*

This is the time required to adjust and set the machine to straighten bar and test its performance. Calculate the cost per metre length by dividing the time taken to set-up with the length of the coil. It assumes that there is one set-up per coil, which is less than actual, as a bar size change can be required a couple of times a day.

*(12) Bends' set-up labour, including on-costs*

This is the cost to set-up the machine to do all bends required in a schedule divided by the number of work pieces for the schedule and again divided by the number of bends in a work piece. All work pieces in a schedule are identical. Calculate an estimate from workplace time and motion study for several different work pieces and persons and averaging the time per bend. The more complicated shapes involving non-90° bends will require a 'complexity factor' to allow for the longer time these take compared to a standard 90° bend. The suggested complexity factor is one (1) for 90° bends and two (2) for all other bends.

*(13) Scrap, including crane movements of bin*

This is the cost of scrap, which runs at 2% of steel bar throughput, or 20mm per 1000mm. Two crane movements, removing scrap and replacing the bin, are also required in the cost. A more accurate scrap rate allowance for each machine is by weighing the actual scrap generated by each machine monthly for a number of months.

*(14) Finished tag moving – crane & labour, including on-costs*

This cost is for moving each finished tag by crane from the machine to its storage space on the floor divided by the number of work pieces in the tag. Allow one crane lift per tag.

*(15) Loading truck/trailer – crane & labour, including on-costs*

This cost is for moving each finished job by crane from its storage space on the floor to the transport vehicle divided by the number of work pieces in the job. Allow one crane lift per job.

*(16) Despatch to customer – paperwork, invoicing*

This cost covers the time spent on each tag by the people in Despatch handling paperwork and inputting into business systems divided by the number of work pieces in the tag. Collect the cost by counting the number of jobs processed in a period by the Despatch personnel and dividing them by the total number of work pieces in the job.

*(17) Finished tag storage – building amortisation & maintenance*

This cost is that required for the floor space within the building including rates, land tax, building maintenance, etc. The floor space relates to the length of the work piece. Estimate the cost per metre length by conducting site surveys of the typical foot print of a range of work piece types and dividing the cost of each type by the total length of the steel in the work piece.

*(18) Invoice processing, including on-costs*

This cost covers the function of creating and processing customer invoices, including rectifying invoice problems. Estimate the cost from historical averages of processing time and allocate per production hour for a work piece. Multiply hourly cost by the estimated hours to produce a work piece. The time for work piece fabrication comes from historical records or by site observation.

*(19) Supervision – Leading Hand & Supervisor, including on-costs*

This is the hourly cost for the leading hand and supervisor multiplied by the estimated time a work piece will take to produce.

*(20) Production Planner, including on-costs*

This is the hourly cost for the Production Planner, multiplied by the estimated hours a work piece will take to produce.

*(21) Senior Management/Accounting costs and on-costs*

This is the hourly cost for senior office staff, multiplied by estimated hours to produce a work piece.

*(22) Hire of factory crane*

This covers the hourly hire for the cranes in the steel bay allocated by machine, multiplied by the estimated hours a work piece will take to produce on the machine.

*(23) Maintenance – crane*

The cost of crane maintenance per hour multiplied by the estimated hours to produce a work piece.

*(24) Maintenance – general costs and building*

This is the cost for non-specific machine maintenance in the steel bay, and associated building, allocated to each machine, multiplied by the estimated hours to produce a work piece.

*(25) Factory lighting*

This is the hourly cost for lighting in the production area, multiplied by the estimated hours to produce a work piece.

*(26) Offices' running costs (Front Office, Production, and Despatch)*

The hourly cost to run the Administration, Despatch and Production Offices and equipment (power, water, air conditioning, cleaning, stationery, etc); multiplied by the estimated hours to produce a work piece.

*(27) Safety*

This is the hourly cost of safety personnel, safety systems, personal protective equipment, etc, multiplied by the estimated hours a work piece will take to produce.

*(28) Quality Control*

This is the hourly cost of quality personnel, systems, documentation, etc, multiplied by the estimated hours a work piece will take to produce.

*(29) Disputes and resolution, including on-costs*

This is an hourly cost allocation for the time and resources taken to resolve disputes on a job. A cost can be estimated using historical data.

*(30) Production Coordinator*

This is the hourly cost for the Production Coordinator, multiplied by the estimated hours a work piece will take to produce.

### **Calculating Crane Lift Cost**

The cranes move job bundles about the production floor and unload/load transport vehicles. Each lift requires the hoisting motor and each movement requires the drive motor. To calculate the cost of a lift it is necessary to determine the power used by the motors while lifting the load and moving it from start to finish.

The weight of the load is variable and can be up to 5 tonnes. However, normal practice is to load transport vehicles in 1-tonne loads for ease of site off-loading. To simplify and standardise the situation for each machine in the production line, a typical weight for each lift will be determined from site observation. The electrical power for a typical lift can be measured by an electrician. Use the cost of power for a lift in the production cost calculation for the relevant steps.

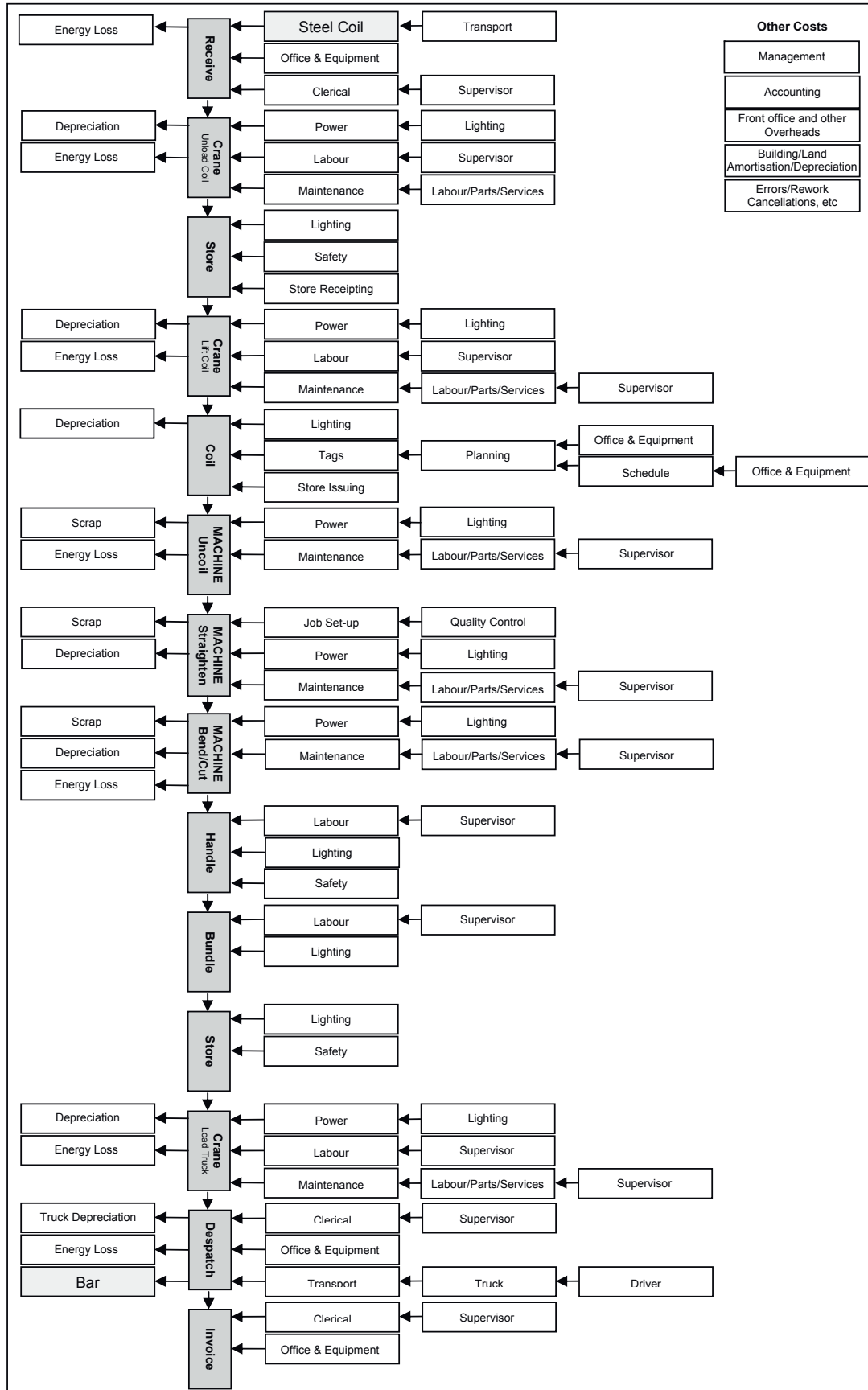


Figure 15.7 – Process Cost and Waste Map for a Production Process.

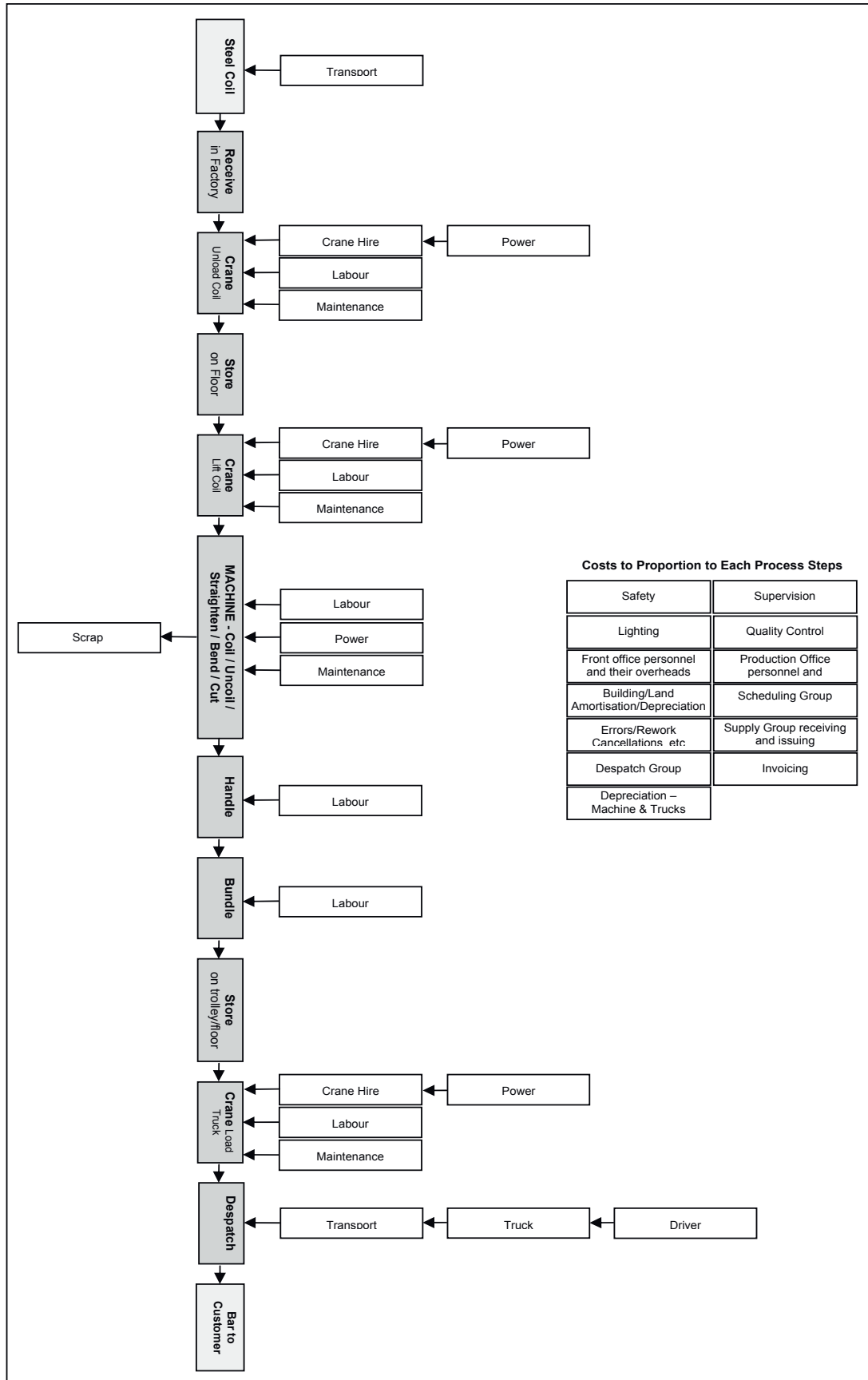


Figure 15.8 – Process Cost Map for a Production Process using Allocations.

## 16. Key Performance Indicators

### Purpose of Key Performance Indicators

There is a story about a great industrialist that wonderfully explains the purpose of key performance indicators. A national magazine interviewed him for an article after years of building his business. The business was performing at world class levels and had been delivering average annual returns of 23% for the last eight years. It was a truly outstanding financial result. The journalist asked the industrialist how he had maintained such a powerful business performance for so long. The industrialist explained his methods.

During the years, as the business grew through both acquisitions and organic growth, he added operations and businesses to the portfolio. In time the business became a major multinational company with significant presence in the market. Clearly, he could not be everywhere at once to guide the many business managers now needed. It was necessary to develop a system to keep him in control while providing direction to the organisation and its thousands of people. Through continuously testing business performance measures, he settled on eight Key Performance Indicators (KPIs) suitable for the organisation, which he tracked each hour on his computer screen. These eight KPIs allowed him to run the entire conglomerate. He would know within half a day if there were problems in any of his businesses by reading the KPI graphs on his screen. If the trends were not right he would follow-up the problem with his managers until it was favourably resolved. Such is the power of Key Performance Indicators. They can proactively identify problems, provide direction and focus, measure performance and identify the necessary corrective actions.

### When to Use Key Performance Indicators

KPIs reflect the efficiency and effectiveness of the conversion process from inputs to desired outputs. Use a KPI to monitor and trend the outcome of a process. Use KPIs to monitor change. Use them to measure the effectiveness with which a strategy is being implemented. When you want to measure effects in, or of, a process, be it a business, industrial or some other type of process, it is appropriate to track it with a key performance indicator. You compare the actual process performance against its ideal performance, or required performance. This permits identification of a discrepancy between what is wanted and what is actually happening. Once recognised, you can investigate both poor and good performances and make changes as necessary. A positive discrepancy can be analysed to learn what factors caused the good result and decide whether to make them standard practice. There is no limit on the range, scale, timing and use of KPIs. They can measure the performance of a single step in a process, right through to evaluating the complete process itself.

### Why Use Key Performance Indicators

A KPI can offer many perspectives on an event. It can permit intense focus and scrutiny, detect changed conditions, score performance, indicate a change from plan, identify potential problems and it can drive improvement. When a KPI monitors and trends a process, the resulting figure tells you something about the process performance and its effectiveness. The KPI should be an accurate, honest reflection of the process efficacy in delivering the outcome. With a reliable KPI measure of performance the effect of a change or a new strategy reflects in the KPI results produced. The KPI will echo if the change improved the result, did nothing, or made it worse. Once you can monitor the effects of a change reliably, repeatedly and accurately by KPIs, they become tools to improve ongoing performance. Simply introduce



the test change into the process and monitor its effect with the KPI. Keep those changes that work and discard those that do not produce useful results. Table 16.1 lists the range of uses for Key Performance Indicators.

Table 16.1 – Uses for Key Performance Indicators.

KPI Purpose	Description	Comments
Focus	monitor the results of actions	When it is not certain that a result is due to a specific set of plans and actions it is useful to introduce KPIs to detect and track what is happening. KPI measures that are thought to be appropriate can be trended over a period of time, and in different situations, to see if they in-fact highlight the relevant factors that are truly important to the successful outcomes from the actions.
Change	track the effect of making a change	If making a change to a process, how is one to know it will be a useful change? This is when an appropriate KPI, or a series of KPIs, will prove or disprove that a change is beneficial. If in fact the change makes matters worse the KPIs will prove it. Change things back to what they were or introduce and test make further changes.
Score	act as a means to measure progress toward achievement	Often the organisation's aim is simply to gradually improve what they do. In such cases the current performance becomes the base line for improvement and all future performances aim at being better than the last result.
Track	when you must meet set targets	When a target is set, it becomes critical to track the efforts used to meet the target. Put suitable KPIs into place to monitor the effects of the organisation's processes on meeting the targets.
Predict	proactively warn of future performance	In every organisation, there are people who are aware of the 'danger signs' that forewarn of future problems. Turn these indicators into KPIs that purposefully track and monitor, to prevent and reduce the risk of future failures.
Improve	drive continuous improvement	Where organisations have several similar operations, it is valuable to introduce identical KPIs into each workplace. This allows comparisons between groups. One group will always outperform the rest. With that group identified, investigate why it outperforms and introduce its methods into the other operations. In this way, the KPI system continually improves the organisation as a whole.

### Which Key Performance Indicators

A KPI is often a mathematical ratio of one number over another, though it does not need to be. A single numerical count, or the recording of a completed number of actions, is suitable for many situations. When written as a ratio the KPI compares the current result against a previous result or a set target. The previous result or the target is the denominator that goes on the bottom line of the ratio. The current result is the numerator and goes on the top line of the ratio. Below is the typical way to calculate a ratio-type KPI.

$$\text{KPI ratio} = \frac{\text{Current result}}{\text{Previous result (or set target)}}$$

Or to identify the size of a change between past and present the KPI is written as:

$$\text{KPI ratio} = \frac{\text{Current result} - \text{Previous result (or set target)}}{\text{Previous result (or set target)}}$$

The choice of a KPI is dependent on the perspective you want to investigate. The industrialist mentioned at the beginning of the chapter was concerned to detect changes early so that he could make corrections before poor performance impacted on business returns. The KPIs were a proactive warning device. He would have selected data generated very early in the business process that reflected complications and losses arising later in his business. It is equally valid to use KPIs to reflect the issues that caused a problem. In that case the KPI is used to fault-find and highlight trouble spots to address and remove from the process. By removing problems the process efficiency is improved.

### **How to Develop Key Performance Indicators**

The perspective taken when developing a KPI dictates the KPIs use. Its purpose affects the formula and the constituents chosen, when to measure them in the process, and how to use them to control performance. KPIs need to be relevant and meaningful to the performance monitored. Do not try and draw ‘a long bow’ to infer conclusions not directly supported by the KPI results. It is better to find a more appropriate, believable KPI, or introduce additional KPIs with the purpose of identifying and clarifying an uncertain situation, than to guess a conclusion.

Selecting the right Key Performance Indicator is critical to managing the desired performance. The KPI(s) must track the outcome(s) required. Equally important is to select the right factors, parameters or variables for collection and monitoring. For example, if on time delivery to customers is important, a suitable KPI would be to measure ‘Required Delivery Date’ verse ‘Actual Delivery Date’. It would be less useful to track ‘Planned Despatch Date’ verses ‘Actual Despatch Date’ since a product shipped when planned could go astray during transport. It could get to the client late. Yet the KPI based on Despatch Date would appear acceptable, even if it were an unsatisfactory result for the customer. However, if you were tracking the performance of the delivery contractor, then it would be appropriate to use both the Despatch KPI and the Delivery KPI. You could track the reliability of their service in picking up the item on time and in delivering the item on time. If they do not meet a satisfactory target you have proof of their poor performance and can rightfully address the quality of their service with them.

There are five common methods used in selecting suitable KPI’s measures and their constituents. These are the ‘Input vs. Output’ method, the ‘Process Boundary’ method, the ‘Results Focus’ method, the ‘Best-in-Class’ method and the ‘Predict the Future’ method.

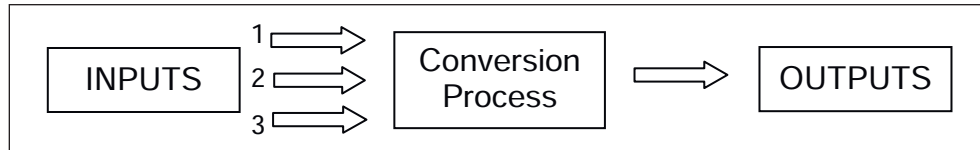
### **Input vs. Output Method**

For direct conversion processes that change an item from one form to another it is common to measure input quantities into the process and the quantities produced from the process. The difference reflects the efficiency and effectiveness of the conversion. For example, a KPI on electrical energy efficiency of a building air conditioning system would measure electrical power into the system against the cooling capacity of the system. Such a measure tells you how well the electricity you are paying for is converted. With this KPI you can trend day by day performance of the air conditioning system. A diagrammatic example of the ‘input vs. output’ approach is Figure 16.1. In the diagram, multiple materials enter the process and multiple outputs leave. You could develop KPIs tracking each input material’s conversion, or an overall KPI tracking the total process. An example KPI might be – Proportion of Raw Material 1 used to make Product 3.



*Figure 16.1 – Multiple Inputs Converted To Multiple Outputs.*

In Figure 16.2, multiple inputs convert to a single output. In this case multiple ‘input vs. output’ KPI’s can measure the effectiveness of individual conversions in the process.



*Figure 16.2 – Multiple Inputs Converted To a Single Output.*

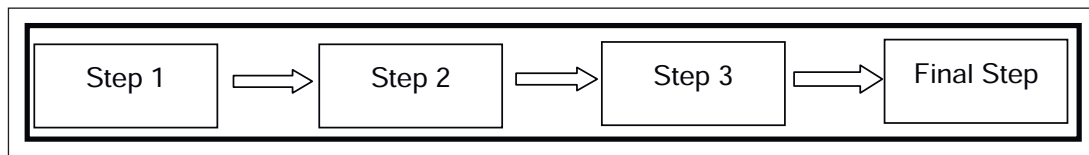
A secondary benefit from an ‘input vs. output’ KPI is to provide you with a benchmark to rate all other equivalent systems. Once you know what your current system performance is you can investigate other methods to see if they are better than the one you have. The other methods maybe within your organisation or maybe they are your competitors. When you find a better performing process you can recognise it and look for what made the difference between your methods and the other. The ‘input vs. output’ approach drives improvement to use existing resources better. Once you can measure the efficiency of a conversion reliably and accurately you have a ‘tool’ to test changes to further improve the process.

### **Process Boundary Method**

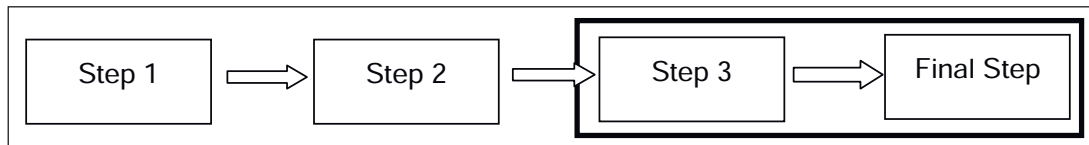
Business or industrial processes can be represented on paper as a series of progressive steps linked one to the other in a process flow diagram. An example is a process logic flowchart for a manufacturing plant, or a flow chart for the processing of accident insurance claims in an insurance company. With the process flow shown on paper, a boundary is draw around the steps to monitor.

Many organisations already have their processes laid-out step-fashion in their quality system documentation. Most manufacturers have their processes laid-out in drawings. It is a simple matter to get copies of those documents and draw the KPI boundaries around what you want to measure. If there are no formal diagrams of the process flows you need to create them. It requires the people who know the various parts of the process well to sit down with pen and paper and flow chart the process. As the process develops on paper include the various inputs and outputs from each step. Once completed the flow diagrams are drawn and become official company quality documents to be controlled and up-dated.

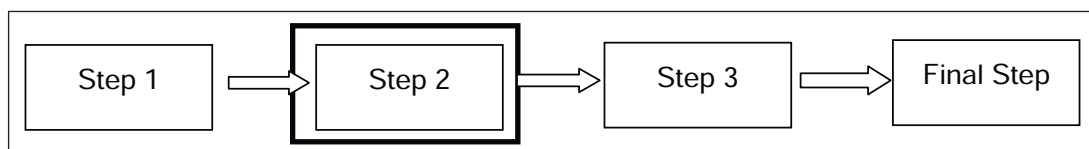
Select KPIs that reflect what materials, documents or other inputs cross into the boundary region verses the materials, documents or outputs that come out of the boundary region. The process boundary approach typically results in multiple KPIs. The majority of businesses, organisational and industrial processes require monitoring several key factors at the same time. It is unlikely that one KPI alone will be sufficiently sound and robust to reflect all the factors affecting a process. Figures 16.3, 16.4 and 16.5 show how the process boundary method applies in a variety of situations. Draw the boundary to measure an entire process or the individual steps within a process.



*Figure 16.3 – Process Boundary Applied Across an Entire Operation.*

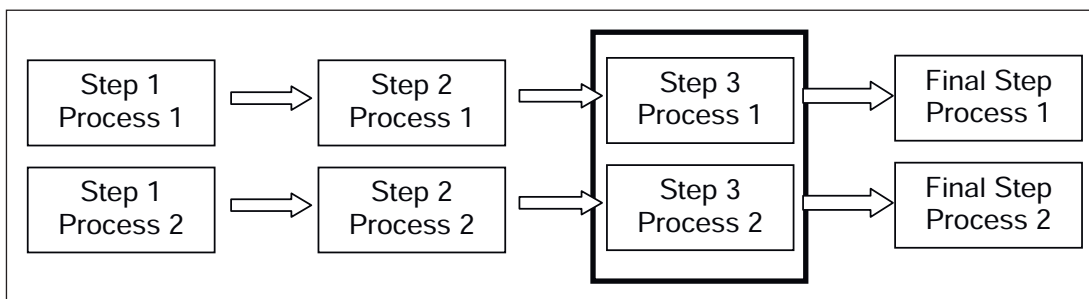


*Figure 16.4 – Process Boundary Applied Across Part of an Operation.*



*Figure 16.5 – Process Boundary Applied Across a Step in an Operation.*

The Process Boundary Method is ideal for comparing process changes, or procedural changes, to evaluate their effect against another similar process. Figure 16.6 shows two processes compared by using the same KPI. One process would typically be the ‘control’ and the other process would be the test case which is changed. Once the boundaries are drawn, the various inputs and outputs for use in the KPIs are, by default, set and you will use them.



*Figure 16.6 – Using Process Boundary Method Used to Compare Across Processes.*

Multiple KPIs can be combined into one ‘global’ KPI that more simply represents the entire group’s performance. An example of a ‘global’ KPI often used to measure manufacturing equipment performance is ‘Overall Equipment Effectiveness’ (OEE). OEE combines KPIs that measure production quality, production throughput and time available for production. The one measure blends the effects of the three individual factors into one number that reflects how the entire operation performed. The full KPI for OEE is below as an example of a single number that reflects multiple factors in an operation or process.

$$\text{OEE} = \text{Availability} \times \text{Performance Rate} \times \text{Quality Rate}$$

**Availability** – Percent of scheduled production (a measure of reliability) or calendar hours 24/7/365 (a measure of equipment utilisation), that equipment is available for production.

$$\text{Availability} = \frac{\text{Hours equipment was available to be used in the time period}}{\text{Total hours for period}}$$

Measures the equipment uptime (actual time that it was in production, or was ready for production) divided by the time that the equipment could be used (usually total shift hours) as a percent. (Equipment utilisation is different. It is actual production time divided by total calendar time.) Along with determining this KPI, it would also be necessary to record the causes of the losses and their frequency. Each of the causes can then be analysed and plans put into place to eliminate them.

**Performance Rate** – Percent of parts produced per time frame of the maximum Original Equipment Manufacturer (OEM) rated production rate. If the OEM specification is not available use the best known production rate over three consecutive runs.

$$\text{Performance Rate} = \frac{\text{Actual production output in the time period}}{\text{OEM rated production output for period}}$$

This measures the percentage of available time that the equipment is producing product at its theoretical speed for each individual product. It measures speed losses regardless of cause (E.g. inefficient batching, machine jams). Along with determining this KPI, it would also be necessary to record the causes of the losses and their frequency. Those causes can then be analysed and plans put into place to eliminate them.

**Quality Rate** – Percent of in-specification parts out of total parts produced per the time frame.

$$\text{Quality Rate} = \frac{\text{Number of parts in specification for the time period}}{\text{Total number of parts produced in period}}$$

This measures the percent of the total output that is good. Along with determining this KPI, it would also be necessary to record the causes of the waste and the frequency. Each of the causes can then be analysed and plans put into place to eliminate them. It is necessary to address all product quality losses, including those due to production, handling, engineering design, etc that produced rework and scrap, otherwise no improvements will be permanent.

**OEE Example:** Availability (0.7) x Performance Rate (0.8) x Quality Rate (0.9) = 50% (which is a terrible result when compared to the world-class manufacturing benchmark of 90%)

KPIs like Overall Equipment Effectiveness become a benchmark target that:

- focus on improving the performance of machinery, plant and equipment already owned.
- find the areas for greatest improvement to provide the greatest return on investment.
- show how improvements in the process, such as changeovers, quality, machine reliability improvements, working through breaks, etc, will affect productivity.

## Results Focus Method

This method requires that a target be set which becomes the goal for the individual, workgroup, department or organisation to hit. The target is the required result. When a specified performance output is set it becomes the only acceptable benchmark. It measures if the results meet the minimum requirements. The late quality guru, W. Edwards Deming, would abhor this KPI – it directly contravenes the spirit of his 14 Points of Management by placing quotas on people. But this KPI can be made to comply with his requirement if it is used to improve the process and methods and not to measure people's productivity. In that case the

focus is on achieving a set target by intentionally forcing change to happen. The method is also known as ‘push the limit’, and can lead to world-class break-throughs.

The results focused approach flavoured with Deming’s insight is very powerful, as it sends a clear signal that all past practices are open for review if changing them will lead to achieving the result. Often sales departments use it when quotas are set for product sales. Operating departments use it when production targets or quality targets are set. The target becomes the least acceptable result and the KPI tracks ongoing performance. Implicit in the results focused approach is the need to question the current process used to hit the target. If a target is not being met using the current process and systems, then changes are required that will produce the intended results. The results focused approach can create harsh and stressful work environments if managed badly. Yet if managed well it can introduce inspiration and adventure into the workday.

### **Best in Class Method**

This approach for determining KPIs is relatively simple. You find those KPIs and performance targets used by the best organisations in the industry and adopt them for yourself. The one difficulty may be establishing systems within your operation to provide the data needed to measure the KPIs. Typically, ‘best in class’ organisations have already gone through significant changes which your operation has not yet been through. You may not have the same systems as they have and so cannot provide identical information for equivalency of comparison. This will necessitate introducing changes to your existing data collection processes so that the information is in a form that lets you truly compare your business against the best in your industry. The ‘best in class’ KPIs provide encouragement to employees and managers since they already have an example of a successful operation using them. All that they are required to do is try and catch-up with the best by developing a better operation. This makes introducing changes clearly justifiable and much easier.

### **Predict the Future Method**

You can choose KPIs that predict your business future. These indicators measure the efforts put into improvement initiatives. For example, improving equipment reliability will increase production as downtime falls. But to increase reliability you must increase the technical skills and knowledge of the people running and maintaining the equipment. Increasing the amount of employee technical training, and improving its content, will produce employees capable of improving the reliability of their equipment. By using a KPI that measures the amount of technical and maintenance training these employees get, you would be gauging how well the plant will improve in future. Measure improvement effort with one KPI and have a second KPI to measure actual performance change.



*Figure 15.7 – Measure Improvement Effort to Gauge the Direction of Future Outputs.*

### **Good KPIs – Bad KPIs**

A good KPI is believable and reflects the true situation in all circumstances. A bad KPI is one that can give you a false impression. For example, a KPI that measures actual results against



planned results is rife for manipulation and presenting falsehoods. An example of a ‘bad’ KPI is below.

$$\frac{\text{Percentage Planned Production Completed}}{\text{Production Completed}} = \frac{\text{Production Completed in the Period}}{\text{Total Production Planned in the Period}} \quad (\times 100)$$

It is easy to get great results with this KPI. Just do not plan to do a lot of work in the period. You can guarantee results close to 100%. People will manipulate this KPI to make management happy. Try and select KPIs that will only deliver the facts and the truth. If you use ‘bad’ KPIs that are manipulable, include additional KPIs that prove their veracity and robustness to see the whole ‘picture’ of the situation. With the ‘bad’ Percentage of Planned Production Completed KPI example above, it is necessary to have a second KPI that also measures the production load to check that the planned production does in fact load the facility fully to ‘name-plate’ capacity. With both measures presented together, it would then clearly indicate how well the production equipment was actually being utilised, as well as how well the operation ran.

### **Gathering and Collecting Information for KPIs**

Part of selecting a KPI measure is to identify where the ongoing performance data will come from, how it is collected and when. If the data is not currently collected someone will need to be appointed to gather it and provide it in a suitable form.

Usually the clerical function of compiling data delegates to a lower level employee than those using the KPI. It is critical that they are given the time to properly collect the information, collate it correctly and believably, then provide it in a usable form to put straight into the KPI. In some cases a manager may collect data themselves in order to get a fuller understanding of what is truly happening. Finding the facts for oneself is to be encouraged. When determining a KPI it is critical to record the causes of discrepancies and problems, along with the frequency of their occurrence. The purpose of a KPI is to highlight a problem and decide if it needs removing. That means capturing the problems and their effects to quantify and cost their consequences. Each of the causes can then be analysed for their impact on the operation and plans can be developed to address them based on their priority and urgency.

Creation of numerical data is normally easy, as performance figures and completion dates are usually required on many organisational reports. Collating the data into a usable form can be expensive and time consuming where no such systems presently exist. Where completely new data is required, there needs to be a great deal of planning and preparation done to introduce the new data collection requirements and methods into the current work processes. Because of the disruption and start-up errors that will occur, it is preferred to work with data already available in an operation than introduce additional data collection. However, if the importance of the data is critical to the future success of the organisation, then its inherent value justifies making whatever changes are necessary to allow the collection of the relevant information.

You can reduce time recording and recovering data by introducing computerisation into the lowest level of the organisation where the data comes from. By computerising data collection it is quicker and simpler to gather it and to interrogate its contents. It also allows development of various KPIs presenting different information from the same records.

### **Data Integrity**

The data you use in KPIs must be unquestionably correct. Collecting data is easy. Collecting data that is a true reflection of what actually happens is much harder. It is critical to ensure that



the information collected is actually used in creating the KPI. Collecting unnecessary or wrong information is a complete waste of time, people and money. The stories of monthly reports generated and not actually used by anyone are common in too many organisations.

Issues of data integrity require managers to specify exactly what information is to be gathered and how it displays. It is not a clerk's role to ensure the KPI information is the correct one to use in the first place. The manager is responsible to set up the KPI system, to define the parameters to measure, and to specify the base data needed to develop the KPI. The clerk is only responsible to follow the specifications and requirements put in place by the manager.

### **Industry Data**

KPI's that are trended against benchmarks require a benchmark to be established. The benchmark figures come from industry and corporate bodies or professional organisations. Another source can be bureaus of statistics or recognised data collection organisations.

### **Best in Class Data**

When organisations are striving to improve themselves and move toward best-in-class performance it is necessary to know the best-in-class results. Specialist consultancies that conduct benchmarking are available and will provide the results for a fee. Possibly consultants with long and broad experience in an industry will know what world-class performance is for the industry. Occasionally the best in class measures are available at industry conventions and presentations. Usually copies of white papers are available after the presentation. Other avenues to find best-in-class benchmarks include industry magazine articles and researching industry websites.

### **Self-Developed Data**

In many cases you can develop KPIs to improve future results without reference to external parties or benchmarks. You select and apply KPIs that use existing data available to the organisation. If no appropriate data is present it must be developed and new collection methods and reports put into place.

### **Frequency of Data Collection**

How often do you need to collect KPI data? Your answer to that question will define how much time and resources to put into developing your KPI system and its reports. KPIs measuring a time component will require a collection frequency to match the time parameter – minutes, hours, days, weeks, months and years.

The amount of data generated for a KPI is proportional to its reporting frequency and the volume of data provided. You will need suitable storage capacity and access to the records required. You will also need people with the time and skills to develop the associated reports and charts by the reporting date.

### **Presenting KPI's – make them visual**

A KPI can be as simple as a single number, through to multiple lines on a graph, or strings of results in a table. KPI reports can be a single page in length, through to a multi-page document. Where possible it is best to present KPI results in a graph. Human beings receive most sensory data through their eyes. Our brains are excellent at detecting changes and variation. But the

brain can handle only 5 or 6 pieces of information at one time. These natural traits make graphic formats using colour, contrast and clarity preferred to using numerical lists. As well as showing the current KPIs, the presentation must also show either historical trends or the benchmark target. It is only by comparing the reported value against a known performance that a true comparison of achievement can be made. Three of many ways to present KPI trends are in Figures 16.8, 16.9 and 16.10.

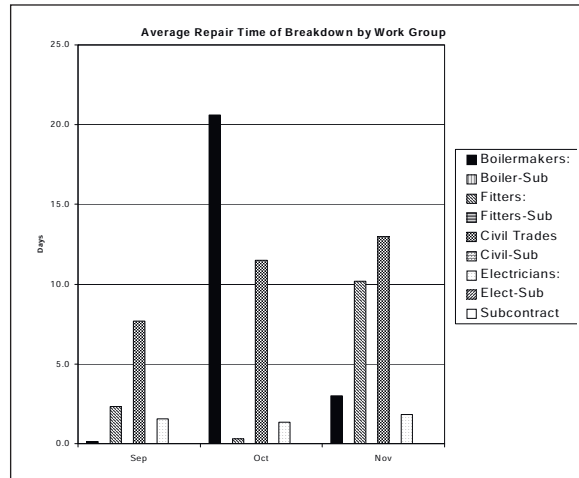


Figure 16.8 – Bar Chart of a Long-Term Continuous Improvement Initiative.

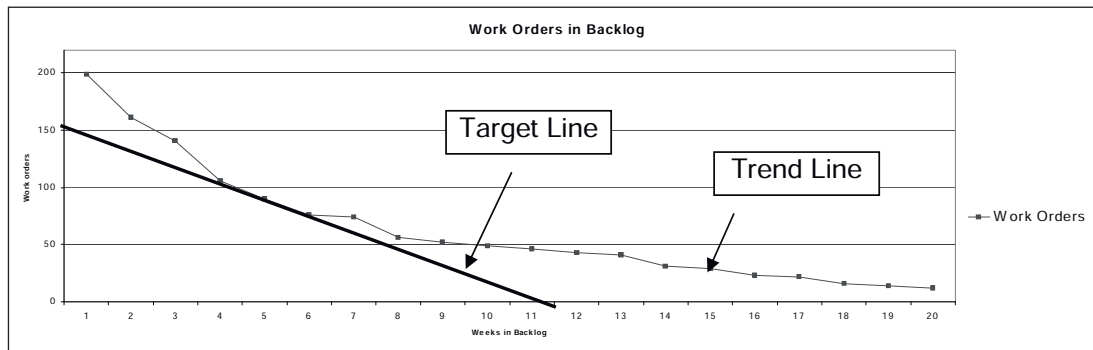


Figure 16.9 – Trending Graph Showing Current Performance against Target.

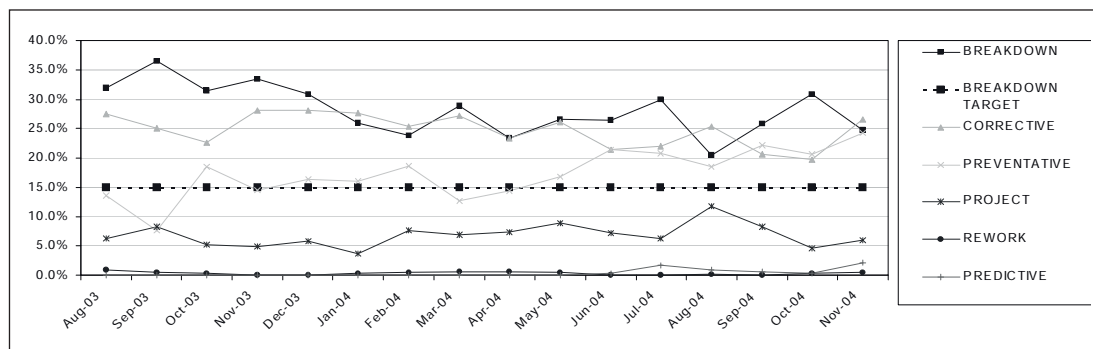


Figure 16.10 – Trending Graph Showing Multiple KPI's on One Graph Including Targets.

## **How to Use Key Performance Indicators**

Key Performance Indicators trend performance. Performance is the result of actions taken, and actions are the result of decisions made. You use KPIs to help people make decisions, or to check on the effect of the decisions people have made. A KPI will tell you if the decisions taken and the subsequent actions have produced a change. Hopefully the change has been beneficial.

KPIs can be used to aid in improving the decision-making of all your people. Make KPIs available to all persons who can gain benefit from knowing the result. People will self-correct and adjust their practices based upon the KPI. It may require some time for some people to change their work methods and practices. In such cases continue pointing out that no beneficial change has yet occurred and that is unacceptable for the future wellbeing of the person, workgroup, department or organisation.

If a KPI result is not an improvement your people will take that to heart and begin looking for ways to better the result next time. This requires encouragement and the opportunity to discuss ideas that will bring about improvements. Make time to let everyone affected by the need for a change to be involved in deciding how to make the change. If they are not involved they will unconsciously block the efforts of others. A participatory approach has a better chance to get commitment and acceptance from all than forcing change on people. It will also be the quickest way to find a good, lasting solution to the issues. If the result is on or above expectation your people will see it as an endorsement of their efforts and want to continue and improve what they do. Reward people proportionate to the progress made.

## **Managing Performance with KPI's**

KPIs are used to purposely feedback and feed-forward critical information in a timely manner to make changes in a process. Without KPIs monitoring a process, the process is not in control. A process can be horribly inefficient and ineffective, terribly costly to the organisation, but still performed continually because there are no measures to judge the worth of its results. KPIs provide a check on progress, they provide direction and they provide data to make sound decisions.

Once there is a KPI there will be people responsible for its attainment. A KPI reflects performance. Some people fear under-achievement, while others will see the KPI as a challenge to make them strive. The proper use of KPIs is not to cause pain to people but to help them to find ways to improve the process they are in charge of so that it produces the required results. KPIs bring a means to measure the effects of actions performed in a process. If the actions do not deliver the required results then scrutinise and review them to determine what part of the performance was not effective. With the issues identified, there needs to be an action plan, with time limits and individual responsibilities, put into place to rectify the situation.

Realise that KPIs will cause changes in people's behaviour. Recognise the good changes and the people who lead them. Recognise the group if success was a group effort. Be fair in your reward and spend according to the benefit the change has brought the organisation. Bad behaviours also need identification and their effects made public so that all can learn from them. But do not publicly punish the individuals involved in poor behaviour or performance, deal privately using support, encouragement and training to develop the appropriate behaviours. If in the end the individual is clearly unsuited to a task you need to move them into work in which they can excel.

## **Introducing KPI's into the Workplace**

When introducing KPIs into a workplace it is necessary to explain their purpose, the workplace changes that may result from them, and the input required by the people in the workplace to

collect them and manage to them. People will have a natural concern with changes in their workday and workplace. Most people want improvement and they will accept changes that they believe will help the organisation or themselves. When introducing KPIs talk about the improvements and benefits they will bring. Privately, openly and truthfully explain to each person impacted by the KPI – whether collecting the data, analysing the data or managing by the KPI – the specifics of how the KPI is used and the effect it could have on them. You want their acceptance and support in using the KPI and you will most likely get that if they are fully aware of how it impacts them.

Anytime there is hesitation with the use or introduction of KPI reporting it is best to request a trial period, after which there is a final assessment made on its continued use. The trial period should be a minimum of six reporting period's duration. By then people will have been through the introduction phase and started to realise the value of the KPI, if there is any.

### **KPI Alignment**

To get the greatest benefit from using KPIs it is best to align them so a KPI acts to direct and reinforce common goals and purpose. The KPIs should cascade down from Organisational, to Departmental, to Work Group and finally to the Personal level. In this way everyone works toward the same aims. To help explain where they fit in the business show the KPIs in the organisation as a hierarchy from top to bottom.

That does not stop the use of KPIs to detect problems and resolve them. KPIs for that purpose are often temporary and only used until the issue is addressed. KPIs that drive an organisation are comparatively permanent and in use for many years. When an organisation's needs change the KPIs also change to match the new focus and direction.

### **Organisational KPIs**

At the organisational level KPIs meet stakeholder requirements and corporate goals. Organisational KPIs can be a mix of financial, community, governmental and operational measures that track performance against set targets. These KPIs reflect the entire organisation's performance. The KPIs are a compilation of many factors and influences. A good structure for an organisational KPI is one that hierarchically subdivides into its component parts. These components allow further breakdown and analysis. By delving deeper through the make-up of the KPI it should be possible to highlight the problem factors and isolate them for closer investigation.

Each department, workgroup and individual should be producing outputs in-line with the organisation's goals. If the KPIs cascade down from the highest levels of the organisation to the lowest then alignment and shared focus is present throughout the operation.

### **Department KPIs**

Departmental KPIs typically are about efficient and effective use of available resources. They highlight opportunities to improve and streamline processes. They also can act to increase 'silo mentality' and drive one department to damage the performance of other departments as they strive to reach their targets. This was one of the effects that the late W. Edwards Deming wanted to remove with his 14 Points of Management.

## Work Group KPIs

KPIs applied to a work group focus the group on working together to achieve a suitable level of performance. They act to promote team work and higher efficiency amongst team members. They also can act to increase ‘silo mentality’ and drive one work group to damage the performance of other groups.

## Personal KPIs

The purpose of KPIs used to manage at a personal level is to guide individual performance. For the KPI to be valid the outcome must be under the control of the individual. Typically, factors such as time, throughput, quality, frequency, accuracy, cleanliness, safety, time keeping, etc. are the responsibility of the individual. By selecting suitable KPIs the individual is aware if their performance meets the necessary standard.

Be cautious with using personal KPIs. It is unfair and useless to attribute system results to individuals. Only special cause issues maybe due to a person. All common cause problems are due to the system and these cannot be changed by an employee, they are the sole responsibility of management to address <sup>70</sup>.

## Sample Maintenance KPIs

Table 16.1 lists a range of KPIs commonly used in maintenance management to track performance and trend progress of improvement efforts <sup>71</sup>.

*Table 16.1 – Maintenance Key Performance Indicators.*

<u>Overall Measures</u>	Percent Uptime Total Maintenance Cost (TMC) as a % of Estimated Replacement Value
<u>Reliability of Equipment</u>	Reliability Professionals per Maintainer Mean Time Between Failure (MTBF) % Emergency Work Estimated Replacement Value (ERV) / Maintainer Training Days (Development/Refresher) / Maintainer
<u>Quality and Speed of Execution/Response</u>	Maintenance Work Force Weeks Backlog Percent Planned Work Maintainers per Planner Schedule Compliance
<u>Maintenance Costs</u>	Stores Investment as a Percent of ERV Percent Overtime Maintenance Labor Cost as a Percent of TMC Contractor Maintenance Labor Cost as a Percent of TMC
<u>Prediction of Failure</u>	Percent PPM Work Percent PPM Schedule Compliance Percent Emergency Work

<sup>70</sup> Deming, W. Edwards, ‘Out of the Crisis’, MIT Press, London, England, 2000 edition.

<sup>71</sup> Maximising Operational Efficiency Presentation, E. I. Du Pont de Nemours and Co, 2004.

## **17. Mining Your Maintenance History**

This chapter shows you how to take the data collected in your maintenance work order system and refine it, then analyse it and liberate the hugely valuable information it contains. Once you find and understand the precious information in your maintenance work order history you have the facts needed to solve your equipment reliability problems and deliver improved production performance. The information you find when you interrogate maintenance history lets you highlight new business opportunities and new means of plant and equipment improvement. For example, you could use the information to draw attention to better ways to design and select equipment, or purchase and manage spares, or to identify job planning loop-holes that could be improved to make work more efficient.

It is likely that you will want to re-design a lot of your equipment. You may even decide to re-engineer your production processes and your business systems once you discover what they have done to your business. It is almost certain that your maintenance work orders contain many opportunities to discover new ways to solve long-standing equipment problems and improve production plant operation. The information you unearth can enrich your people and your company in a positive fashion. Use the information to get the management and financial support you need to change for the better.

### **Why Analyse Your Maintenance Work Orders**

A good maintenance work order report has the history of the maintenance job, the parts used, a record of the damage, and the associated costs and resources used on the job. With cost data, work-time data, resources data and operating-impact data, you have the information to measure productivity, efficiency, value-add and effectiveness of the maintenance effort on the operation. These are operating performance measures of powerful value for any business. They become accessible by first collecting, and later interrogating, your maintenance work order histories. If you have a collection of complete and accurate maintenance work order history spanning long periods, you have good information to measure the worth of that maintenance to the organisation. You also have a complete list of all the maintenance and reliability problems in your operation. Provided your maintenance system records the full costs, resources and times needed to do a maintenance job, you can be confident that the information drawn from it will reflect the truth. The work order history is a factual data base that through careful analysis lets you identify opportunities to solve equipment problems and improve current operating and maintenance practices for the betterment of all concerned. By analysing maintenance work orders you can detect hidden trends. Such as an increase in breakdown work, or a rise in costs compared to previous periods. There are numerous messages about the operation, the equipment, and their performance hidden in your work order system. Even if your maintenance work order system only records the repairman's report there is still enough information there to let you identify equipment reliability problems and justify their solving.

### **How to Analyse Your Work Orders**

Analysing maintenance work orders (MWO) involves searching for themes and patterns in their history. One-off variations in maintenance jobs where a thing did not go well, or there were errors made, are not useful for changing the philosophy of doing maintenance (unless many of your maintenance jobs keep going bad; then you have a business system issue to solve quickly!).

Maintenance work analysis uses historical work orders from a particular period and specific facility area, or process circuit, or manufacturing line, etc. By using data over a reasonable length of time the effects and trends, and perhaps even their causes, become evident. It is the



trends that are important, as they reflect the persistent factors in your 'system' that impact on it over the long-term. If there are systematic problems you need to identify them and correct the business system, since it is because of the business system that you have the problems. Occasional repairs that go over the expected cost will not send you broke. What will send you broke is a business system that does not recognise what causes the costs and has nothing in-place to control those causes. If the maintenance system itself is a failure then you need to recognise that from your maintenance history and move to fix it quickly!

### **Periods to Use for Analysis**

Typical time periods used are the financial year or the calendar year. Other useful periods are financial quarter or calendar quarter, particularly if you are looking for evidence of short-term performance changes. Long-term periods include 2, 5 and 10 years. These are good for investigating equipment reliability issues, or the long-term effect of changes in methods and philosophies applied in the organisation. One means to view these long trends is with the 'Long-Term Improvement Plan' spreadsheet provided on the CD accompanying this book. Its purpose is to show a historic record of the frequency of problems and their impact on the operation over the years. It provides evidence to justify their removal by redesign or the purchase of more reliable equipment. Future improvement projects are included on the spreadsheet to show a business' commitment to expend resources and capital to make the operation more reliable and lower cost. When analysing specific items of equipment the period can be the equipment's entire working life. This may span several decades. If during that time the equipment was improved, the analyst needs to know, so they are aware when the history altered because of the improvement. Otherwise, they may use the maintenance history incorrectly and advise that a problem exists when it does not.

The easiest way to interrogate historical work orders is to place all the records over a period from a section of facility into spreadsheet software. If the maintenance work orders are in electronic form exporting the data into a suitable spreadsheet is normally a straight-forward task. Where the maintenance work orders are in a manual system get the necessary information entered into the spreadsheet. Record the work order data in spreadsheet columns suitably titled for the information. Typical headings include equipment number, equipment name, work order number, trades required, date requested, date completed, job description, job history or corrective action, material costs, labour costs, resources costs, along with other relevant information related to the analysis. A simple example of such a spreadsheet is Table 17.1.

If you are still using a verbal request system for maintenance work the analysis is much more difficult and less meaningful. However, it is possible to do a basic level of analysis by interviewing your operators and maintainers. Taking equipment items one at a time and then their assemblies and components one at a time, record peoples' recollections of problems over the years and the maintenance done to fix them. Develop the analysis categories you require before the interviews so that you know what questions to ask them. Another useful repository of plant and equipment history are the operations and maintenance shift logbooks used to record daily issues and to communicate between people and shifts. Read these carefully looking for equipment problems and dates and describe the details in the spreadsheet.

### **Using Existing Categories on the Maintenance Work Order for Analysis**

Usually a maintenance work order has a range of information recorded on it as it moves through the maintenance process from generation to performance and finally closure. This information allows the work order to be analysed by those categories. When transferring the data from the work order system into a spreadsheet make sure that data names, or titles, come



across with the data and are put as the column headings of the spreadsheet. Without the column headings you will not be able to recognise what the data represents. Hide unnecessary columns in the spreadsheet in order to show only the columns you require. It is more convenient to hide columns instead of deleting them so that a column is available for a later analysis if necessary. Once you delete a column the data is lost and you must start the spreadsheet again if later you find you did need the information.

### **Introducing New Analysis Categories and Codes**

At times, the work order may not have the search criteria you want to use as one of its standard fields. In such situations it is necessary to introduce the category you require into the spreadsheet with its own column. You then go through each work order one by one and categorise it by the new category. For example, Table 17.2 introduces two new columns into the spreadsheet for two new categories – Job Type and Work Order Cause. The two new categories are themselves divided into a series of meaningful codes. The Work Order Cause Category codes consists of:

- P** – Process related cause where the work order was a result of a process problem.
- D** – Design related causes where the WO was most probably due to a design decision.
- I** – Installation related cause from poor installation practices.
- M** – Maintenance related causes due to real maintenance issues.
- O** – Operating related cause from operator errors.
- S** – Statutory requirement that require maintenance by law.
- E** – Else causes where no obvious explanation was evident.

The Work Order Cause category designates each work order by the likely reason for its raising. It highlights that a good proportion of maintenance was due to design, installation and operating issues that then flowed onto cause maintenance costs. A lot of your maintenance cost is most likely not due to the equipment, but from knock-on effects caused by other reasons.

### **The Job Type Category codes covered:**

- R** – Regular and normal maintenance work that is fair and reasonable to expect.
- I** – Improvement to plant or capital project related work.
- F** – Failure and breakdown repair related work.
- A** – Assistance provided to operations work but not related to maintenance.
- P** – Preventative related works, which were usually PM's and statutory jobs.

The Job Type category allows the work orders generated in the plant to be analysed to determine how much of the work performed by the maintenance group was truly a maintenance cost. A lot of your maintenance costs may not be strictly maintenance. Rather your maintenance crew do non-maintenance duties that take up their time and their costs are booked to maintenance. Read each work order through and give a code to represent its category. The requirement to read each work order and select a code to classify it can take a great amount of time. Yet if you introduce new categories to classify the maintenance work orders, it makes sense to spend the time and effort to classify them correctly so that you get a good, reliable and accurate analysis. Once you have trustworthy information you will have the confidence to use it to make decisions.

The organisation decides and defines what extra analysis categories they need. The analyst doing the work needs to know the categories to use and the meaning of each code in the category. The

Table 17.1 – Example of a Basic Maintenance Work Order Analysis Spreadsheet.

Asset No	Short Desc.	work_grp	cmpl_date	labour	mtl_cost	con_cost	workreq	corr_action
WLW	Willow Hill Facility	CIVILS	26/08/04	\$0	\$1,281	\$1,281	Please get the roof on the storage shed repaired/made safe as the clear cladding has become loose.	Skylight replaced
WLW	Willow Hill Facility	FITTERS	21/07/04	\$170	\$148	\$250	Carry out lubrication round per attached route sheet	Replace 2 auto-lubes - topped up g/boxes
WLW	Willow Hill Facility	CIVILS	02/12/04	\$255	\$335	\$488	Please get the plastic curtains on the storage shed repaired, some are loose, and one has come off.	As per work requested
WLW	Willow Hill Facility	BOILERMAKERS	04/08/04	\$467	\$340	\$620	Can we please have some hose racks made up for behind Facility west wall.	50x6 ss flat bar brackets mounted to concrete base of wall. 6m 300mm cable tray hose rack
WLW	Willow Hill Facility	BOILERMAKERS	06/08/04	\$117	\$20	\$90	Could we please have a small tool box fitted to the tower floor to store tools in safely, this is required by a hazard report.	Tool box was bolted to floor as requested
WLW	Willow Hill Facility	BOILERMAKERS	04/08/04	\$233	\$40	\$180	We require a small steel cabinet made up and installed by the large roller door to put safety gear in ( gloves and dust masks )	Cabinet made
WLW	Willow Hill Facility	ELECTRICIANS	12/08/04	\$1,006	\$110	\$714	Please have the power point located below WLW-10 relocated to the west side.	Moved GPO to where operators required it.
WLW	Willow Hill Facility	FITTERS	29/07/04	\$58	\$94	\$112	Can we please get the automatic grease cartridges on the whole of the crushing circuit checked and replaced if necessary	Replaced 2 cartridges
WLWAC-6A	Air Compressor	SUBCONTRACT	18/08/04	\$83	\$0	\$270	Please service air compressor	Changed separator within compressor
WLWAC-6A	Air Compressor	FITTERS	20/01/05	\$83	\$0	\$300	Please service air compressor	Assisted serviceman
WLWAC-6B	Air Compressor	FITTERS	15/07/04	\$83	\$0	\$745	Service air compressor	Assisted contractor with compressor service

Table 17.2 – Adding Additional Analysis Categories For Work Order Interrogation.

Asset No	Short Desc.	work_grp	cmpl_date	WO Cause	Job Type	labour	mtl_cost	con_cost	workreq	corr_action
WLW	Willow Hill Facility	FITTERS	30/03/05	O	A	\$85	\$0	\$0	Please remove the bank/spade that at the spool piece so we can begin to run directly from tank.	Fitted spool piece back on
WLW	Willow Hill Facility	FITTERS	29/03/05	P	A	\$43	\$20	\$33	Please set up the hoses from tank to pump so we can bypass tank	fitted spool pieces and hoses
WLWAD-4	ADVANCED SCREW UNIT	FITTERS	22/03/05	O	A	\$375	\$0	\$225	Can we please have the pins removed from the housing	removed pins turned upside down to allow flow
WLWAD-4	ADVANCED SCREW UNIT	FITTERS	01/12/04	O	A	\$85	\$0	\$51	Get all the pins turned around in the morning.	Removed all pins around
WLWCF-3	Filter	FITTERS	05/05/04	O	A	\$417	\$60	\$310	Can we please have the flexible shroud inside the filter replaced	FITTED NEW SHROUD
WLWCF-3	Filter	ELECTRICIANS	21/05/04	O	A	\$85	\$10	\$36	Please re-fit encoder during outage and lock in place.	REATTACHED ENCODER
WLWCF-3	Filter	ELECTRICIANS	30/06/04	O	A	\$128	\$0	\$77	Please have the cake thickness sensor adjusted to decrease the cake thickness.	ADJUSTED CAKE THICKNESS SENSOR AS REQUIRED BY OPERATIONS
WLWCF-3	Filter	ELECTRICIANS	01/10/04	O	A	\$67	\$0	\$20	Move cake thickness to increase the cake thickness by about 20-30mm.	ADJUSTED CAKE THICKNESS BY 25MM APPROX
WLWCF-3	Filter	ELECTRICIANS	15/03/05	O	A	\$260	\$0	\$156	Move the level switch for larger cake thickness by 30mm	ADJUSTED BY OPERATORS

person selected to read and classify maintenance work orders into new codes must know the plant and equipment maintenance history very well. It requires a thorough knowledge of the equipment and the maintenance practices in your organisation for the correct classification of work orders into new categories. Typically this is someone like an experienced maintenance supervisor or even the plant engineer or maintenance engineer.

### **Conducting the Analysis of Your MWOs**

The first step in analysis is to decide what you are looking for. You develop the spreadsheet structure to suit the questions you need to answer. When you know the questions you want answered you will extract the right information from your Computerised Maintenance Management System (CMMS), or manual systems, into the spreadsheet. You can also add any missing categories needed to analyse the spreadsheet data. Once the maintenance order history is listed under the headings you require, use the sorting functions of the spreadsheet package to collect and arrange the data into meaningful sense. You will need to know the appropriate spreadsheet software instructions. Some common questions include:

- a) What proportion of maintenance work is breakdown, corrective, preventative, etc?
- b) How often is an equipment item failing?
- c) What is causing the maintenance required? (Here you develop meaningful codes to use when categorising the work orders)
- d) What parts are regularly replaced?
- e) What outside services and contractors are regularly hired?

The range of questions is dependent on the data available for analysis. Questions involving parts usage or subcontractor hire require access to information in inventory management and purchasing systems. It may be more beneficial to use other data bases and information systems if they are better suited to the query. It may not be sensible to find answers to questions through MWO history analysis if the relevant data is already in other parts of your management information systems.

### **Identifying Reoccurring Problems and Opportunities to Improve**

It is important to know how well directed the maintenance efforts are, or if they can be more finely tuned. Analysis of categories such as costs, times, maintenance problems, etc will draw attention to hidden issues. Sorting a spreadsheet by category and category code captures work orders of the same code and identifies them as having a common reason to be in the group. The category code represents an issue that you are interested in knowing about and identifies work orders related to that issue. Once the work orders are coded you review each for additional insights into the specific issues related to the code group. It may take a substantial amount of time, possibly days, to conduct a truly thorough analysis. You will later recover the cost of the time invested with the improvements that will flow from the analysis. The effort to understand maintenance actions and effects, and to look for ways to improve equipment care, delivers paybacks for years to come in streamlined processes, improved equipment performance and higher rates of production at lower costs <sup>72</sup>.

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<sup>72</sup> Fitchett, Don, Sondalini, Mike, 'True Downtime Cost', 2nd Edition, [www.BIN95.com](http://www.BIN95.com), 2006.

## Keyword Searching

An alternative to the use of categories and codes is to use the existing text on the work order and search for keywords within the text. For example, searching for ‘bearing(s)’ in the work order text will identify those work orders where the word appears in the text. If there were many references to bearing problems for an item of equipment then you would have justification to investigate the causes and look at solving them. The information may support spending money to improve the lubrication program or change machine bearing protection. The keyword search approach is most often fruitful in work request description text and the job completion comments from the repairman. Identifying maintenance issues through work order keyword searching can highlight hidden equipment and system problems not previously recognised because they occurred infrequently.

## Pareto Charting the Frequency of Repetitive Problems

Maintenance work orders can be categorised by the frequency an issue arises and shown in a Pareto chart to highlight their occurrence. A Pareto chart makes issues visible. They work for individual equipment or for entire processes. Figure 17.1 is an example for the diaphragm pump operating problems from Table 17.3. The Pareto chart highlights that the pump was changed-out numerous times and there were blockage problems with the process. These types of analyses are ideal for identifying repetitive problems that an operation is living with.

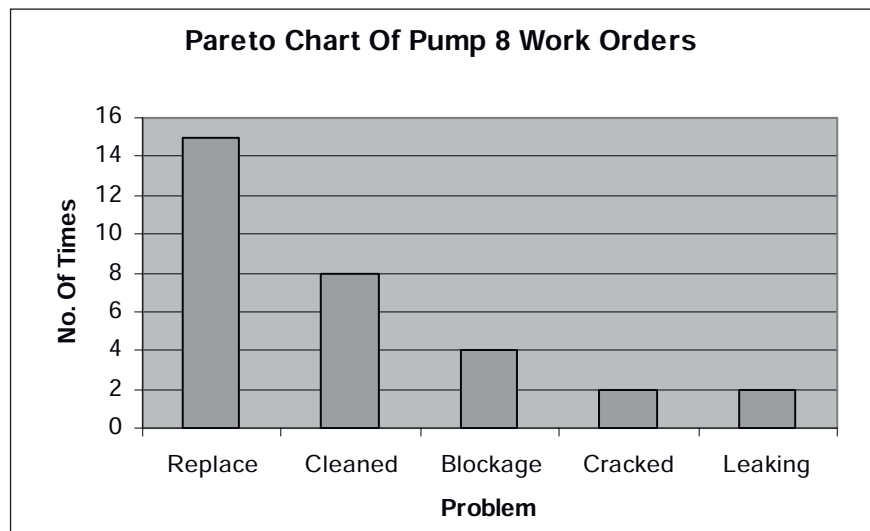


Figure 17.1 – Pareto of Diaphragm Pump Failures.

A Pareto chart could compare costs per repair, hours to repair, or any other category on the spreadsheet. How the data should be analysed for information and understanding of the issue is entirely up to the analyst in response to the investigation brief.

## Timeline Frequency Analysis (Charting Time Between Failure)

A Time Series Table, like Table 17.4, involves looking at the dates of work on equipment and laying out the dates for repetitive work orders in horizontal rows for all to see. The process of building the Time Series Table is straightforward. Choose the category of interest or categorise the work orders by category, then record the work order start dates in a row of the spreadsheet. Gradually you see the scale of the problem by the number of entries on the rows

and the frequency of the problem by the number of repair dates. You can go a step further and find the direct costs of living with the problem. If the work orders record cost information it is a simple matter to collect the total costs for each work order and tally them to present a very clear picture of the direct expense of the problem. (The cost on a work order does not include the full DAFT Cost to the organisation. Until all DAFT costs are included in the costing exercise you do not yet have the true downtime cost to the business.)

The issue dates and completion dates used on work orders are useful for identify the failure frequency for a plant item. Table 17.5 shows the completion dates rearranged in calendar order, and the days between each work order. The 'Days Between' failure column is also shown as a time series in Figure 17.2. As a plot it is visually graphic and attention grabbing. This item of plant clearly caused a great deal of trouble for the operation throughout its operating life. In one case, it failed three times on the same day! The history of failure makes it clear that the problem is an operating issue where process material blocks the pump. Changing the pump with a spare was the solution most often taken. But the frequency of failure is so extreme that the problem was important enough to design-out of the process and a straining screen was installed to catch solids. Using a timeline lets you highlight the real impact of a problem's frequency. If failures are excessive or expensive this analysis strikingly identifies need for improvement.

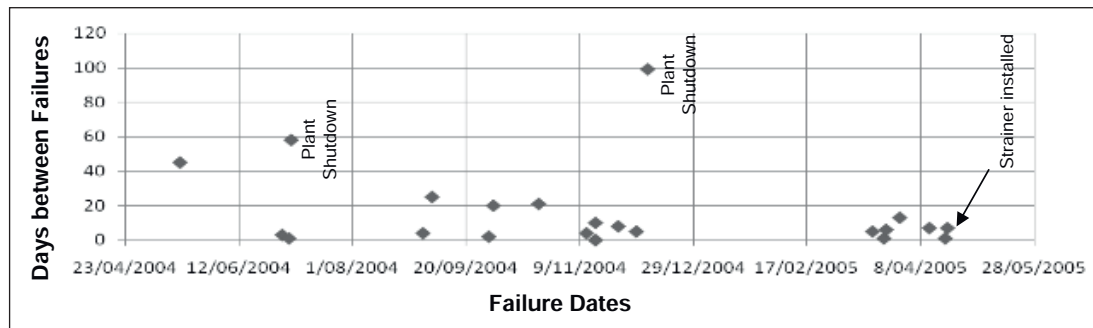


Figure 17.2 – Failure History Timeline.

### Ratio Comparisons for Benchmarking and Continuous Improvement

With all work orders for a period and/or item of plant gathered in a spreadsheet it is opportune to develop management ratios of operational and equipment performance. The choice of ratios and their aim is up to the organisation's management. They can be used to benchmark against others in your industry or as a means to track your continuous improvement. Ratios include:

$$\text{Breakdown Ratio} = \frac{\text{Breakdown WOs}}{\text{Total WOs}}$$

$$\text{Preventative Maintenance Ratio} = \frac{\text{PM WOs}}{\text{Total WOs}}$$

$$\text{Proportion of Time Maintaining} = \frac{\text{Total Time Spent on Maintenance WOs}}{\text{Total of Time for Maintenance Crew}}$$

$$\text{Use of Contractors Ratio} = \frac{\text{Total of Contractor Time on WOs}}{\text{Total of Time on All WOs}}$$

Any analysis category would make useful key performance indicator ratios if improvements were to be undertaken. Two examples might be:

$$\% \text{ MWO's Due to Design Problems} = \frac{\text{No. of WOs Attributed to Design Issues}}{\text{Total WOs}}$$

$$\% \text{ MWO's Due to Operating Errors} = \frac{\text{No. of WOs Attributed to Operator Error}}{\text{Total WOs}}$$

### **Analysing Equipment Reliability Issues**

Another way to analyse MWOs is by taking one item of equipment and reviewing its maintenance history to focus on the issues affecting its performance. This allows you to identify what these issues are, their effect on the operation and their cost to production. For example, it may be useful to identify causes of repetitive failures, or why there are continual replacements of parts, and design-out the problem causing the maintenance. Once you have categories for the causes of equipment operating and maintenance problems you can develop solutions to address the worst of them. When investigating equipment reliability issues you require all maintenance history available on the item of plant from its start-up date, or for as long as there is history. Having equipment history that reflects the operation and maintenance of the equipment over a long time provides a good amount of factual data to work with. It will show any persistent issues that have been with the equipment during its life.

Table 17.6 is a spreadsheet for a centrifugal pump with persistent failures identified and classified over a year. They were due to three failure modes. One was dead-heading where a programming error closed the discharge valve when instructed by the process control computer but the pump ran-on and did not turn-off in the program. The second was where the operators ran the pump in manual to empty the tank and then left the pump running so that it was run dry and destroyed the mechanical seal. The third was a process problem where product scaled the impeller and suction entrance when the pump stopped and jammed the impeller in place. It was only after analysing and putting a cost to the problems, identifying their production time losses and associated expenses, that the true production impact of the pump failures was recognised. Once it was clear that the failures were causing serious maintenance costs concerted efforts were made to stop the failures. Without the maintenance history data to provide evidence of cost and failure frequency, it would have been difficult to get production support to fix the real causes of the problems.

### **Identifying with Fault Codes**

Each equipment failure will have a reason. It is important to find the real cause of the problem and fix it. Analysing maintenance work orders with fault codes is a powerful way to find failure problems. With the work order history in a spreadsheet you read each work order text, both the request and the repairman's report, looking for keywords related to the job. It soon becomes apparent what problems the equipment has suffered during its operating life by the continual use of the same words, or words of similar meaning, in the text. These problems become the fault codes to classify all work orders. An example of using identifying fault codes is Table 17.6.



If your MWO already contains fault codes as part of your standard procedures, still read a selection of about 20% of the work orders to see if the fault codes used are reliable and accurate. If they are not accurate then reclassify all the MWOs with apt fault codes.

To gain additional insights it is also valuable to read the maintenance crew logbooks and the operator or production shift logbooks for the period concerned. The operations logbooks and maintenance crew shift records can contain valuable details on problems that were not recorded in the maintenance work order history. This information can be of great use in understanding what process problems, operating problems and shift crew problems existed prior to equipment failures.

### **Analysing Equipment Reliability**

If a part or equipment item is failing too soon you investigate the reason. Provided there are reliable dates of failures for each failure mode, and no failures by a mode have been missed, it is possible to do engineering reliability on the failure. With each failure mode identified you have the necessary information to conduct reliability modelling and analysis to interrogate the failure modes so you can solve them.

Software programs are available to trend equipment reliability and develop probability of failure curves. For example, if you have parts usage dates of age-related failures the software can be used to determine the optimal period between parts replacement. The software optimises the cost and date to do preventative maintenance and advises when to replace the part to minimise downtime losses.

Before using reliability prediction software carry-out a timeline frequency analysis for each failure mode and see if the periods between failures already identify obvious problems for investigation. Use timeline analysis to identify when equipment is not providing sufficient service life. This stimulates engineering and management focus to make resources available to fix problems.

Reliability engineering is now a well developed discipline and a powerful additional tool available to understand what happens to equipment. There are serious pitfalls to be aware of in analysing equipment reliability and it is the realm of people well-educated in probability mathematics and trained in the use and limitations of the methods applied. Develop in-house university qualified reliability specialists or establish a contractual relationship with an experienced service provider. Chapter 18 provides a short introduction to Reliability Engineering.

### **Analysing Maintenance Costs and Time**

Equipment maintenance costs are easily analysed once put into a spreadsheet. You can group costs by any category on the spreadsheet. If you want total costs for breakdowns and preventive maintenance on a machine during a particular period, you would sort the spreadsheet into those categories and subtotal the costs. An example is Table 17.7 showing subtotal costs for equipment. With subtotals by category you can proportion costs against total cost. For example, this can be the cost of equipment maintenance in one year against the cost for its lifetime, or the cost of preventive maintenance for the equipment in a period as a proportion of all maintenance spent on it in the period.

This approach is useful to analyse the repair time recorded on maintenance work orders (also known as Mean Time To Repair – MTTR). Long repair times mean equipment was not available for production. Where the average times to do a job vary greatly it justifies an investigation. Analysis of the work order times will identify problems and allow people to propose solutions for issues affecting the work.

One concern with using historic work order times is that unless people are paid on the times recorded on the work orders the times will not be accurate. They will be a rough estimate and not itemised by use of the time. When you analyse labour time data from maintenance work orders be aware that there will be inaccurate recording of the real times of all resources and labour used on the job. Provided you are willing to use the time analysis results as an indication of effort, and not an absolute measure, you may get some meaningful results.

### **Capital Justification Including True Downtime Costs**

There will be many reasons for the problems discovered by your analysis. What is important is to find strong financial justifications to make the necessary changes to get rid of them. Improvements will only be supported by management if there is a strong financial case in their favour. As you do your analyses always keep the thought in the back of your mind of how to find the true and full costs that these problems are causing your organisation.

Your work order history should have records of all the costs incurred by the maintenance department during a repair. You will not have true costs if they don't include allowances for all the maintenance overhead expenses required to deliver maintenance. Costs for supervision, planning, management, accountancy support, payroll support, stores management support, etc, need to be recorded to each work order. If the maintenance cost is high enough it will justify investing money, time and resources to remove or reduce the problem.

The maintenance costs noted in the CMMS are not the true costs of a problem to your company. DAFT Cost analysis warns us that even if all overhead costs were included in a MWO it would still be short of the true business-wide cost by around 1,000%! The shortfall is the knock-on costs of failure incurred by the entire business. You may need to find them all to justify capital improvement or changes to business processes.

When preparing capital justifications to fix the problems discovered by your analysis you will be required to quote real, provable costs. These costs will be part of what you find as you do the analysis. But be sure that somewhere in your report you also tell readers about the other DAFT Costs that you could not find during your analysis. They are there, hidden in the business-wide waste caused by every failure.

### **Results from Case Study Investigation**

Throughout this chapter the examples shown reflected a real analysis performed on an operating plant. The results of the study are summarised in Table 17.8. From it maintenance and process improvement strategies were identified to address the low plant reliability that was caused by the numerous random failures and poor manufacturing process control.

Table 17.3 – Identifying Causes of Failure and Showing Them in a Pareto Chart.

Asset No	Short Desc.	WO Cause	Job Type	Problem	workreq	corr_action
WLWPU-8	Cleaning pump	P	F	Replace	Please replace pump as it is not pumping.	removed pump and
WLWPU-8	Cleaning pump	P	F	Replace	CHANGE OUT PUMP 8 WITH SPARE	As Per Work Requested -
WLWPU-8	Cleaning pump	P	F	Replace	Please repair/ replace Pump 8 as it is not pumping.	Replaced Pump 8 with recon pump
WLWPU-8	Cleaning pump	P	F	Leaking	PUMP 8 is leaking can we please have it fixed.	REPLACE 1.5" BOLTS FOR 1.75" AS THE BOLTS WERE STRIPPED. PUMP IS TURNING OFF AFTER VALVE HAS BEEN CLOSED SEEN ELECTRICIAN ABOUT CHANGING PLC SO DISCHARGE V/V STAYS OPEN 5-10SEC LONGER.
WLWPU-8	Cleaning pump	P	F	Replace	REMOVE Pump 8 AND REPAIR OR REPLACE	REPLACED Pump 8 WITH SPARE
WLWPU-8	Cleaning pump	P	F	Blockage	REPAIR ON CHANGEOVER Pump 8	REMOVED BLOCKED PUMP AND INSTALLED RECON
WLWPU-8	Cleaning pump	P	F	Replace Cleaned	Can we please have stripped and cleaned out.	Pump 8 CHANGED OUT AND CLEANED PIPEWORK - STRIPPED PUMP
WLWPU-8	Cleaning pump	P	F	Leaking	PUMP 8 LEAKING AND NOT PUMPING PROPERLY - INVESTIGATE AND/OR REPLACE	REPLACED PUMP
WLWPU-8	Cleaning pump	P	F	Replace	Pump 8 not pumping, please inspect and repair/ replace	exchanged pump - cleaned pipe work
WLWPU-8	Cleaning pump	P	F	Cracked	PUMP 8 is cracked can we please have it changed out.	
WLWPU-8	Cleaning pump	P	F	Blockage	check Pump 8 and associated pipe work for blockage	REPLACED PUMP AND CLEANED PIPEWORK
WLWPU-8	Cleaning pump	P	F	Blockage	Pump 8 is blocked/not working and the bottom of tank 8 is full of hard solids. Please remove and repair the pump and make it possible for the operators to clean out the bottom of tank 8.	As Per Work Requested
WLWPU-8	Cleaning pump	P	F	Replace	Please order a new PUMP 8	allow 2 weeks delivery
WLWPU-8	Cleaning pump	P	F	Replace	PLEASE REPLACE Pump 8	Relocate old pump and install. Check suction lines - clear.
WLWPU-8	Cleaning pump	P	F	Replace	PUMP 8 is not pumping. can we please get this fixed/replaced.	As Per Work Requested
WLWPU-8	Cleaning pump	P	F	Cleaned	PUMP 8 is not pumping can we please have it fixed or replaced.	Stripped pump once removed cleaned out and refitted
WLWPU-8	Cleaning pump	P	F	Blockage	PUMP 8 is blocked up again and TANK 8 is overflowing. Please inspect and repair.	Change out pump
WLWPU-8	Cleaning pump	P	F	Replace	Can we please get Pump 8 changed out.	As Per Work Requested
WLWPU-8	Cleaning pump	P	F	Cleaned	Pump 8 is not pumping can we please have it fixed can we also have the top of TK-8 removed as it is full of solids.	STRIPPED PUMP 8 CLEANED REBUILT
WLWPU-8	Cleaning pump	P	F	Replace Cleaned	Pump is not pumping properly can we please have it looked at.	REPLACE WITH RECON PUMP - CLEANED OLD PUMP
WLWPU-8	Cleaning pump	P	F	Replace	Can we please get PUMP 8 changed out	changed out pump and replaced with recon
WLWPU-8	Cleaning pump	P	F	Replace	Can we please get PUMP 8 changed out as it is not pumping correctly	changed out Pump 8
WLWPU-8	Cleaning pump	P	F	Replace	Tk-8 is overflowing again. Please replace Pump 8 and clean out tank 8.	REMOVED PUMP 8 - REBUILT.
WLWPU-8	Cleaning pump	P	F	Cracked	repair to Pump 8 cracked and leaking badly	As Per Work Requested -

Table 17.4 – Time Series Table Using The Work Order Creation Dates.

Asset No.	Equipment Description	Work Order Description	Work Order Creation Dates											
			Apr-03	Oct-03	Nov-03	Aug-04	Jul-03	Aug-03	Feb-04	Aug-03	Aug-03	Aug-03	Oct-03	May-04
WLWBN-41	Product Bin	replace dust bags												
WLWBN-42	Product Hopper	bagging head valve not operating	Dec-03	Jun-04	Jul-04	Aug-04								
WLWCF-3	Screen	remove and unblock feed pipe	Mar-03	Mar-03	May-03	Jul-03	Jul-03	Feb-04						
WLWCF-3	Screen	fix/adjust level setting	May-03	May-03	May-03	Aug-03	Aug-03	Aug-03	Aug-03	Oct-03	May-04			
WLWCF-3	Screen	clean/replace spray nozzles	May-03	Jul-03	Jul-03	Aug-03	Aug-03	Aug-03	Aug-03	Sep-03	Oct-03			Mar-05
WLWCF-3	Screen	adjust cake level sensor	May-03	Mar-04	Jun-04	Oct-04	Mar-05							
WLWCV-11	weigh feeder to mixing tank	VSD tripped, reset drive	Mar-03	Mar-03	May-03	May-03	Jun-03	Jun-03	Jul-03					
WLWCV-11	weigh feeder to mixing tank	seal leaking on hopper	Feb-03	Nov-03	Dec-03									
WLWDR-4	paddle unit	inspect, clean air ductwork	Apr-03	Jun-03										
WLWDR-4	paddle unit	unblock pipe work from dust collector	May-03	Jun-03	Jun-03	Jun-03								
WLWDR-4	paddle unit	replace gasket/seals on steam line	Aug-03	Nov-03	Dec-03	Jan-04	Apr-04	Apr-04	Apr-04	Jul-04	Aug-04	Oct-04	Mar-05	
WLWDR-4	paddle unit	bearing replaced	Aug-04	Aug-04	May-05									
WLWEV-6(HE)	Heat Exchanger	Replace heat exchanger	Mar-03	May-03	Nov-03	Oct-04								
WLWEV-6(PU1)	Liquor Recycle Pump	Repair/Replace seal	Feb-03	May-03	Jul-03	Mar-04	Jul-04	Jul-04	Aug-04	Mar-05				
WLWEV-6(PU3)	Product pump	Repair/Replace seal	May-03	Nov-03										
WLWEV-6(VP1)	Vacuum Pump	Replace seal	Jun-03	Apr-05										
WLWFL-2A	Leaf filter unit	Low level sensor faulty	Mar-03	Mar-03	Jan-04	May-04								
WLWFL-2A	Leaf filter unit	Seal replacement	May-03	Aug-03	Oct-03	Apr-04								
WLWFL-2A	Leaf filter unit	clean, inspect pipe for blockages	Feb-03	Mar-03	Apr-04									
WLWFL-2A	Leaf filter unit	replace filter leaves	Jan-04	Feb-04	Apr-04									
WLWFL-2A	Leaf filter unit	Drain ball valve replaced	Apr-04	Jan-04	Dec-04	Jan-05								

Table 17.5 – Timeline Frequency Analysis or Mean Time Between Failure (MTBF) Charting.

Asset No	cmpl_date	workreq	corr_action	Dates in Order	Days Between
WLWPU-8	04/12/04	Please replace pump as it is not pumping.	removed pump and	17/05/04	0
WLWPU-8	05/07/04	CHANGE OUT PUMP 8 WITH SPARE	As Per Work Requested -	17/07/04	45 (Annual shut)
WLWPU-8	19/04/05	Please repair/ replace Pump 8 as it is not pumping.	Replaced Pump 8 with recon pump	4/07/04	3
WLWPU-8	01/07/04	PUMP 8 is leaking can we please have it fixed.	REPLACE 1.5" BOLTS FOR 1.75" AS THE BOLTS WERE STRIPPED. PUMP IS TURNING OFF AFTER VALVE HAS BEEN CLOSED SEEN ELECTRICIAN ABOUT CHANGING PLC SO DISCHARGE V/V STAYS OPEN 5-10SEC LONGER.	5/07/04	1
WLWPU-8	17/05/04	REMOVE Pump 8 AND REPAIR OR REPLACE	REPLACED Pump 8 WITH SPARE	1/09/04	46
WLWPU-8	04/07/04	REPAIR ON CHANGEOVER Pump 8	REMOVED BLOCKED PUMP AND INSTALLED RECON	5/09/04	4
WLWPU-8	01/09/04	Can we please have stripped and cleaned out.	Pump 8 CHANGED OUT AND CLEANED PIPEWORK - STRIPPED PUMP	30/09/04	25
WLWPU-8	05/09/04	PUMP 8 LEAKING AND NOT PUMPING PROPERLY - INVESTIGATE AND/OR REPLACE	REPLACED PUMP	2/10/04	2
WLWPU-8	02/10/04	Pump 8 not pumping, please inspect and repair/ replace	exchanged pump - cleaned pipe work	22/10/04	20
WLWPU-8	16/11/04	PUMP 8 is cracked can we please have it changed out.		12/11/04	20
WLWPU-8	30/09/04	check Pump 8 and associated pipe work for blockage	REPLACED PUMP AND CLEANED PIPEWORK	16/11/04	4
WLWPU-8	22/10/04	Pump 8 is blocked/not working and the bottom of tank 8 is full of hard solids. Please remove and repair the pump and make it possible for the operators to clean out the bottom of tank 8.	As Per Work Requested	16/11/04	0
WLWPU-8	12/11/04	Please order a new PUMP 8	allow 2 weeks delivery	16/11/04	0
WLWPU-8	16/11/04	PLEASE REPLACE Pump 8	Relocate old pump and install. Check suction lines - clear.	26/11/04	10
WLWPU-8	16/11/04	PUMP 8 is not pumping, can we please get this fixed/replaced.	As Per Work Requested	4/12/04	8
WLWPU-8	26/11/04	PUMP 8 is not pumping can we please have it fixed or replaced.	Stripped pump once removed cleaned out and refitted	9/12/04	5
WLWPU-8	09/12/04	PUMP 8 blocked again and TANK 8 is overflowing. Please inspect and repair.	Change out pump	18/03/05	95 (Plant was Shutdown)
WLWPU-8	27/04/05	Can we please get Pump 8 changed out.	As Per Work Requested	23/03/05	5
WLWPU-8	24/03/05	Pump 8 is not pumping can we please have it fixed can we also have the top of TK-8 removed as it is full of solids.	STRIPPED PUMP 8 CLEANED REBUILT	24/03/05	1
WLWPU-8	18/03/05	Pump is not pumping properly can we please have it looked at.	REPLACE WITH RECON PUMP - CLEANED OLD PUMP	30/03/05	6
WLWPU-8	23/03/05	Can we please get PUMP 8 changed out	changed out pump and replaced with recon	12/04/05	12
WLWPU-8	30/03/05	Can we please get PUMP 8 changed out as it is not pumping correctly	changed out Pump 8	19/04/05	7
WLWPU-8	20/04/05	Tk-8 is overflowing again. Please replace Pump 8 and clean tank 8.	REMOVED PUMP 8 - REBUILT.	20/04/05	1
WLWPU-8	12/04/05	repair to Pump 8 cracked and leaking badly	As Per Work Requested -	27/04/05	7

Table 17.6 – Spreadsheet Identifying Persistent Equipment Reliability Problems With Fault Codes.

Asset NO	Short Desc.	cmpl_date	WO Cause	Job Type	Failure Mode	workreq	corr_action
WLWPU-1	Mixing pump	14/05/04	P	F	Seized	Can we please have the wet end changed out during the shutdown as it is <b>not freely turning</b> on restarting	changed out pump with spare
WLWPU-1	Mixing pump	19/05/04	D	I		Replace existing pump suction spool with new double block and bleed spool	completed in shutdown
WLWPU-1	Mixing pump	16/07/04	O	F	Seal Leak	Please rebuild pump 1 as a spare	overhauled pump due to <b>seal failure</b> . had to realign concentricity from 0.65 to 0.48mm mech seal failure due to broken stationary face, pump had been <b>dead headed</b> .
WLWPU-1	Mixing pump	14/05/04	O	F		The discharge ball valve has a bent shaft can we please replace	replace ball valve on pu-1
WLWPU-1	Mixing pump	08/07/04	M	P	Seal Leak	Inspect drive belts and check for burning, fraying or cracking. Replace if required. Inspect drive pulleys for wear. Check alignment of pulleys and belt tension. Realign and retention if required	This PM not done since pump changed out 6/07/04 due to <b>mech seal failure</b>
WLWPU-1	Mixing pump	07/07/04	M	P	Seal Leak	The seal on PU1 is leaking badly, can we please have this changed out tomorrow while the cleaning circuit is depressurised.	<b>Mech seal failure</b>
WLWPU-1	Mixing pump	06/10/04	P	F	Seized	PU-1 will <b>not turn</b> fix it.	freed up pump with stilsons
WLWPU-1	Mixing pump	22/12/04	O	P	Seized	PU-1 will <b>not turn</b> , it appears to be seized, please get this fixed	pump and line not drained after use - pump freed up
WLWPU-1	Mixing pump	15/02/05	M	F	Seized	WHPU-1 has tripped and will not reset ( might need fitter as support )	check motor history code indicates thermal o/l possibly due to ambient temp. reset running ok - tripped again thermal o/l, current tripping rated limit. <b>suspect impeller</b> . fitted recon pump
WLWPU-1	Mixing pump	02/12/04	M	P		Inspect drive belts and check for burning, fraying or cracking. Replace if required. Inspect drive pulleys for wear. Check alignment of pulleys and belt tension. Realign and retention if required	as per work requested -
WLWPU-1	Mixing pump	19/01/05	M	F		STRIP PUMP AND REBUILD PUMP	overhauled pump, replace old <b>mech seal</b>
WLWPU-1	Mixing pump	26/12/04	P	F	Seized	Pumped tripped, please inspect.	<b>freed up</b> with stilsons
WLWPU-1	Mixing pump	17/01/05	M	F		Please change out pump 1 as the <b>mech seal</b> is leaking.	replaced old pump with spare
WLWPU-1	Mixing pump	09/02/05	M	F	Seal Leak	Pump 1 is <b>leaking from around the shaft</b> . Please inspect and repair	changed over pumps, laser aligned pulleys + tensioned belts to 350 nm. fitted new taper lock and gaskets
WLWPU-1	Mixing pump	11/02/05	M	F	Seal Leak	strip pump and investigate why pump leaked, rebuild pump.	stripped down. cleaned all mating surfaces. fitted new seals and o rings. rebuilt with new <b>mech seal</b> bench tested to 400kpa for 15 mins
WLWPU-1	Mixing pump	18/02/05	M	A		Please remove guard and check the drive pulleys have been replaced in correct position.	removed guard check pulleys ok.
WLWPU-1	Mixing pump	21/04/05	M	F	Seized	to please get pump 1 running	as per work requested -

Table 17.7 – Subtotalling Annual Maintenance Costs by Equipment Item.

Asset No	Short Desc.	work_grp	cmpl_date	labour	mtl_cost	con_cost	workreq	corr_action
WLWBL-6	BOILER	FITTERS	23/06/04	\$263	\$2,563	\$4,892	Strip down boiler for annual inspection Call in independent inspector to do internal inspections and running inspection Call in water treatment people to inspect boiler scale and adjust treatment	DONE ON SHUTDOWN
WLWBL-6	BOILER	ELECTRICIANS	04/05/04	\$700	\$859	\$1,279	Some of the wiring at the back of the boiler at the bottom near the blowdown lines appear to be slightly burnt/melted	WIRING REPLACE IN ANACONDA CABLE
WLWBL-6	BOILER	FITTERS	14/05/04	\$128	\$0	\$38	Can we please have blanks installed in the steam line to heater and drier steam line once the boiler is isolated, can these also be removed at the end of the shutdown.	As Per Work Requested
WLWBL-6	BOILER	ELECTRICIANS	27/10/04	\$85	\$0	\$2,573	Lost power to LED display on the boiler	
WLWBL-6	BOILER	CIVILS-SUB	16/07/04	\$0	\$0	\$3,480	Can we please have the blow down pipe work at the rear of the boiler lagged	INSULATION WAS PUT ON PIPEWORK AND METAL
WLWBL-6	BOILER	CIVIL TRADES	05/08/04	\$170	\$0	\$102	The door on the boiler chemical dosing cabinet has broken off	
WLWBL-6	BOILER	FITTERS-SUB	12/08/04	\$0	\$53	\$568	Please repair steam leak on boiler.	As Per Work Requested -
WLWBL-6	BOILER	CIVIL TRADES	12/08/04	\$0	\$0	\$2,690	Can we please get the flu on the boiler pipes lagged	
WLWBL-6	BOILER	FITTERS	05/10/04	\$85	\$25	\$681	Please have broke sight glasses changed out.	As Per Work Requested -
WLWBL-6	BOILER	ELECTRICIANS	19/10/04	\$85	\$0	\$369	Require some electrical assistance to fix an electrical fault	Assist gas fitter to replace air proven and flame detector.
WLWBL-6	BOILER	FITTERS-SUB	15/01/05	\$300	\$0	\$5,000	Strip down boiler for annual inspection Call in independent inspector to do internal inspections and running inspection Call in water treatment people to inspect boiler scale and adjust treatment	Boiler stripped and inspected. Repairs carried out to refractory inside the boiler. Running tests carried out and checked
WLWBL-6	BOILER	ELECTRICIANS	21/02/05	\$85	\$0	\$0	There is currently no power to the boiler. Please inspect why.	RESET PWR AND OK
<b>WLWBL-6 Total</b>				<b>\$1,901</b>	<b>\$3,500</b>	<b>\$21,672</b>		
WLWTK-6	FEED TANK	FITTERS	02/05/04	\$250	\$250	\$0	PLEASE FIT SPADES TO TANK 6 x 2	As Per Work Requested
WLWTK-6	FEED TANK	FITTERS	03/05/04	\$112	\$186	\$0	Can we please get hose connections installed to enable process condensate to go to the boiler feed water tank	done
WLWTK-6	FEED TANK	FITTERS	20/05/04	\$128	\$150	\$0	TO REMOVE PIPEWORK BETWEEN PUMP AND TANK	
WLWTK-6	FEED TANK	FITTERS	18/04/05	\$128	\$92	\$0	please put manway back on TK6 as per manual work order	As Per Work Requested -
<b>WLWTK-6 Total</b>				<b>\$617</b>	<b>\$658</b>	<b>\$0</b>		



Table 17.8 – Investigation Results.

Category	Code	No of WO's	% of WO's	% Cost	Comments
During the 12-month time period there were 813 work orders raised in the plant.					
Job Type	Improve plant (I)	88	11	20	
<i>The sort of work done on the work order.</i>	Failure correction (F)	350	43	52	
	Assistance (A)	80	10	6	
	Blockage clearing (B)	73	9	7	
	Preventative (P)	220	27	15	These are PM's, condition monitoring and servicing.
WO Cause	Process Issue (P)	142	17.5	27	
<i>The root cause of the work order being raised.</i>	Design Issue (D)	89	11	21	
	Installation Issue (I)	20	2.5	2.5	
	Maintenance Issue (M)	382	47	40	
	Operating Need (O)	138	17	13	
	Statutory Need (S)	16	2	2.5	
	Else (E)	24	3	3	'Else' covers all WO's that did not fit into other codes.
Failure (F)	Process Issue (P)	84	24		
	Design Issue (D)	41	12		
	Installation Issue (I)	14	4		
	Maintenance Issue (M)	175	50		
	Operating Need (O)	6	2		
	Statutory Need (S)	4	1		
	Else (E)	23	7		

### Analysis Interpretation

From the analysis, it appeared that:

1. True maintenance (repair work orders and PM's) was 60% of the work and 67% of cost.
2. Plant improvement work was 11% of the work and 20% of cost.
3. Operating support (Blockage cleans and assistance) was 19% of work and 13% of cost.

Of the repair work orders, it appears that:

4. The cause of 50% of the repairs was a real equipment problem.
5. The cause of 24% of the repairs was process characteristic related.
6. The cause of 16 % of the repairs was a design decision related (12%) or installation quality related (4%) factor.

Of the 813 work orders raised in the twelve months, 220 were for PM's to check for a condition problem with equipment or to do lubrication. There were 88 improvements and these would not repeat again. The remaining 505 were plant-related problems.

One major issue with this plant was its many random, unpredictable problems. The Time Series Table showed several equipment items with recurring equipment problems and others with recurring process problems. In the 12-month period covered by the study there were 105 repeating work orders from the 505-plant related problems. The recurring work was 20% of plant problems. The other 80% were totally random. You could choose to design-out the recurring problems. The random failures would be much more difficult to manage because they occurred without prediction.

You address random failures with precision maintenance and precision operation to prevent defect creating stress; by design selection of equipment that comfortably handles the operating stresses; with preventive maintenance to replace wearing parts, and condition monitoring to detect problems starting. This collection of strategies reduces the chance of having failures and addresses randomness by early detection to permit corrective action to be taken before failure.

A further strategy against random failure is to purposely select critical equipment and design-out the problems in the equipment before they cause trouble. This improves the equipment and designs in the reliability needed for high plant availability. Japanese engineers have a saying, "A new machine is in the worst condition it should ever be." They believe that it is the user's responsibility to modify and improve a machine to be highly reliable for its service. By looking for opportunity to improve your equipment's reliability you are following the advice of the world leaders in equipment reliability.

Because of the above analysis there were new strategies developed to reduce maintenance costs, new plans were created to address the process related problems and a chemical engineer was tasked to solve the process problems. The random failures were addressed by lifting preventive maintenance (PM) and condition monitoring (CM) inspections throughout the plant from 25% to 60% of all work orders. The costs of improvements and capital works, including the maintenance labour component, was capitalised. During the design stage of projects use of Failure Mode and Effects Analysis (FMEA) removed potential downtime causes. The work order analysis brought the organisation's maintenance problems to the surface for resolution.

### **Challenging Old Habits and Ways**

If you are fortunate to have a fully integrated computerised maintenance management system then you can find every cent of value from the maintenance history. Even if a CMMS is not fully integrated with the other business systems, you can get huge value from what information there is. If you have a manual maintenance system there is still great value in those hand-written notes and scrawled list of used parts once they are in a spreadsheet! The time spent analysing work order history is an investment in your company's future. You are on the trail to discover the causes of your problems and to see if there are ways to solve them. That has to be important to the future success of your organisation! If the solutions to the problems are minor costs and not difficult to implement then get on and make the changes to fix them.

The engineering problems you discover are the easy ones to fix. They require some design effort and some money spent on them. They will be easily financed because the DAFT Costs prove how horribly expensive they are. The system-induced and ignorance related problems will be magnitudes harder to solve. Those problems are, unfortunately, the most common cause of failure in a business. The systematic and lack-of-knowledge problems are the ones you must solve if you want a strong, vibrant, healthy organisation with a long-term future. Talk to the people affected by what you discover. Show them the consequences of the problems on the organisation and its business. Immediately enlist their help in solving the easy issues by asking them what they suggest is the best way to resolve them. Do not argue with them or question their suggestions, after all, they know their jobs better than you do. They are the

‘local experts’. Simply support them in their efforts to make the necessary changes. If they have problems give them the opportunity to come back and talk to you about them. That is when you give them your advice, but not until they show you that they need it.

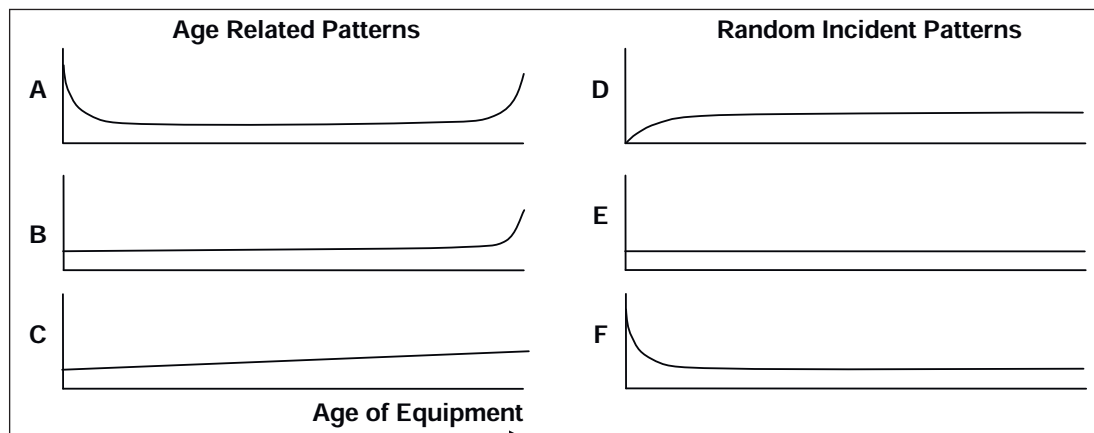
Use the ‘Change To Win’ team approach of involving people in making improvements. The workbook for the ‘Change To Win’ 100-day program is included in the CD accompanying this book. It gets people together working as teams and helps them to become knowledgeable in a problem so they can fix it properly themselves.

## 18. Reliability Growth

Quite literally, you can choose the failure rate you want for your plant and equipment and then put into place the practices and methods that naturally deliver it.

### Failure Patterns and Failure Modes

Equipment failure follows one of the six probability patterns in Figure 18.1, made famous by the 1978 Nolan and Heap study into aircraft equipment failures<sup>73</sup>. Evidence from airline industry maintenance in the 1960s and 70s indicated that together failure patterns D, E and F represented 89% of aircraft equipment failures. With pattern F, showing infant mortality failure, alone representing 68%. Other airlines and the USA Navy conducted similar studies and confirmed the patterns. Though the proportions varied with different industries, patterns D, E and F dominated. The curves highlight that once most equipment are through the early-life period, failure is not age related but is ‘random’ and can happen anytime. This does not mean there is no reason for a failure, there definitely is, but when the event will happen is uncertain. Nolan and Heap questioned the practice of doing regular overhauls, since if most equipment failures (89%) had nothing to do with the age of the equipment, why were parts replaced on a time basis. You could be throwing away a perfectly good part still suitable for many hours of service, and introduce early-life failure from human error.



*Figure 18.1 – Six Failure Patterns for Parts  
(only applies to ‘parts’, not overhauled assemblies).*

The recognition that few equipment failures are age related allowed development of a new methodology in the airline industry called Reliability Centred Maintenance (RCM), where maintenance strategies matched the operating risk caused by failure. Unless the consequence of failure was so severe that it could not be allowed to occur, RCM required proof of failure starting before maintenance was conducted. If failure was unacceptable, or expensive, then equipment was redesigned to remove failure modes. Alternately, age-based refurbishment and fixed time replacement was demanded after set hours of operation and well before parts could fail. All other equipment required condition monitoring to find evidence that maintenance was necessary. RCM allowed preventive maintenance to be replaced by on-condition maintenance.

<sup>73</sup> Nolan, Stanley F, Heap, Howard F., ‘Reliability Centred Maintenance’, Dolby Access Press, 1978.

There is some uncertainty in the veracity of the original analysis used by Nolan and Heap <sup>74</sup>. The 1970s actuarial analysis of failure data incorrectly mixes together parts replacement and complete equipment renewal. Replacing selected parts still leaves those parts not replaced untouched. The old parts contain accumulated stresses and are no longer as strong as new. The weakened older parts are at greater chance of failure from stress incidents than the new, stronger parts. It is not equal to compare the failure rate of equipment repaired by replacing selected parts with equipment fully overhauled and fitted throughout with new parts. This misunderstanding raises questions over the true causes of equipment failure and the proportions of each failure curve.

Because RCM is limited to using maintenance practices to reduce equipment operating risk it is not used in Plant and Equipment Wellness. Equipment risk reduction in Plant and Equipment Wellness is driven by economic considerations of failures. RCM reserves cost analysis only for extreme financial risks. This leads to the same problem as RCFA (Root Cause Failure Analysis) suffers, which is that it is reserved for removing catastrophic failures and so companies continue having catastrophic failures. By doing RCM without knowing the cost of an event before selecting mitigation there is insufficient understanding on which to make good economic risk-based decisions. The restrictions on financial analysis of failure in RCM means a business is using a process that cannot deliver what it wants. The maintenance crew ends up being busy but no one is sure it is actually to the company's benefit.

Plant Wellness uses standard risk management methodology and demands cost be considered for every risk situation. The body of knowledge on risk analysis and management is well accepted, well documented and completely appropriate in industrial situations to rate risk and develop mitigation practices. It is already applied in identifying Equipment Criticality and is a methodology well known to maintenance and project groups. If there is risk and safety management expertise existing in a business those people have the knowledge and skills to be a resource immediately available to the maintenance group for risk analysis.

Plant Wellness uses computers to do DAFT Cost calculations to permit easy manipulation of large amounts of financial data and quick 'what-if' scenario analysis not possible with RCM. Instead of tying up lots of people in a team doing RCM, risk analysis and costing uses one person, with the team being saved for review of the analysis and risk mitigation selection. Risk control in Plant Wellness is required throughout the life cycle and applied by everyone. It is not limited to maintenance activity only.

## Reducing Equipment Parts Failure

Understanding the cause and effect relationships of equipment and operational problems is an essential part of an effective maintenance program. The parts in a piece of equipment can only fail in a limited number of ways or 'failure modes'. A parts-hardware level FMEA finds the likely failure modes and lets people decide what to do. If failures can be detected after initiation by physical inspection, or with condition monitoring, then the problem is corrected before failure. When the DAFT Cost consequences of a failure are unimportant the parts can be let run to destruction and then replaced. Where the consequence of failure is important actions are put into place to prevent the failure. These include defect eliminating precision practices, regular overhauls of parts with age-based failure characteristics, total replace of equipment when key parts approach end-of-life and equipment redesign to remove failure modes.

The purpose of maintenance is to deliver improving equipment reliability. We do that by

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<sup>74</sup> Sherwin, David, 'A Critical Analysis of Reliability Centred Maintenance as a Management Tool', Australian Asset Management Council ICOMS 2000 Presentation.

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. Recall the story of the diesel engines used on a ship that had three times less maintenance cost than identical engines used in a locomotive. Because of the policy decision to de-rate engine duty to 90% of nameplate capacity they saved much operating downtime and maintenance cost. The evidence of successful reliability improvement shows up as falling rates of parts failure and greater operating life of equipment. Figure 18.2 shows the changed failure rate of equipment parts by choice of appropriate policies and use of the required methods.

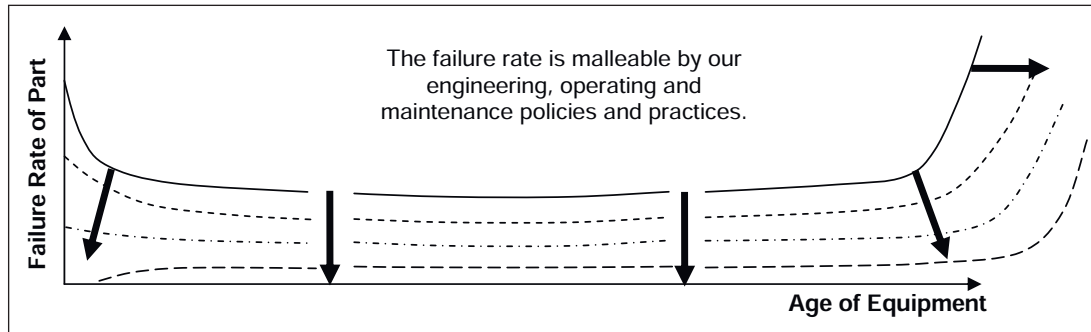


Figure 18.2 – The Rate of Failure is Malleable by Choice of Policies and Practices.

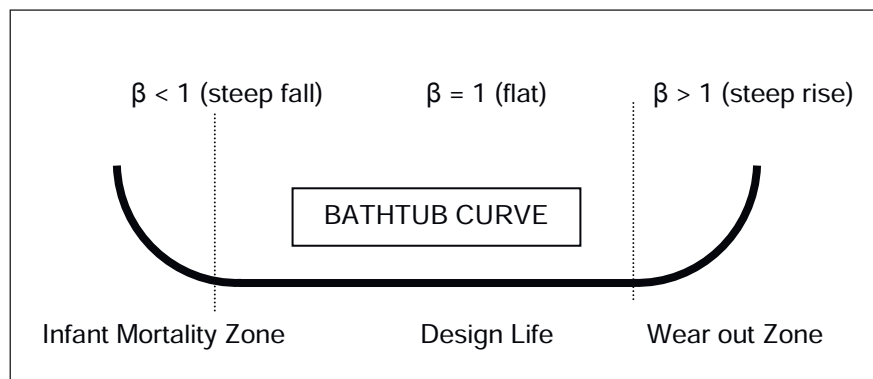


Figure 18.3 – Weibull Wear-out Life Curve.

### Weibull Analysis <sup>75</sup>

Waloddi Weibull identified the Weibull distribution in 1937 while seeking a formula for the failure rate of welds. It is now one of the most commonly used methods for fitting equipment life data and used extensively in the aviation industry to optimise maintenance intervention and select maintenance strategy. The essence of Weibull's work was to discover he could represent the Bathtub Curve of Figure 18.3 using mathematical formula. His equation could mimic the behaviour of a combination of other statistical distributions, which were each of limited use, by changing its shape. It could represent all the zones of the bathtub curve by using the three Weibull parameters – beta  $\beta$  (shape parameter), eta  $\eta$  (life) and gamma  $\gamma$  (start location). Note that the 'beta' used in Weibull Analysis has a different meaning to the

<sup>75</sup> Note: Some of the content for the topic was provided by Michael Drew, Director, ARMS Reliability Engineers, Australia.

'beta' of Crow-AMSAA plots. The Weibull shape parameters provides the owners, users and maintainers of equipment with a tool to use the failure history of their operating plant and predict the behaviour of components and items of equipment replaced as complete units. The analysis directs selection of effective equipment maintenance strategies and design-out efforts to reduce parts failure.

$\beta < 1$  implies infant mortality. Electronic and mechanical components often have high failure rates initially. Some components are purposely 'burnt in' prior to use, while others require careful commissioning after installation. The presence of infant mortality indicates poor training, lack of procedures and poor quality control.

$\beta = 1$  implies random failures. These failures are independent of time and an old part has the same chance of failure as a new part. Maintenance overhauls are not appropriate for random failures. Condition monitoring and inspection are strategies used to detect the onset of failure and then reduce the consequences of failure. This zone is affected by random incidents and accidents. It reflects poor operating procedures, poor risk management and poor materials selection at design.

$1 < \beta < 4$  implies early wear out. You would not expect this type of failure within the design life. Failure mechanisms such as corrosion, erosion, low cycle fatigue and bearing failures fall in this range. Maintenance often involves a periodic rework or life extension task. The shape can be altered by better materials selection, by degradation management and by good control of operating practices.

$\beta > 4$  are wear-out or end of life failures. They should not appear in the design life. Age related failures include stress corrosion cracking, creep, high cycle fatigue, and erosion. Appropriate maintenance is often the renewal of the item with new.

An ideal profile for equipment is to have a negligible failure probability throughout its operating life followed by a steep beta that predicts the replacement age. Figure 18.4 shows such a profile.

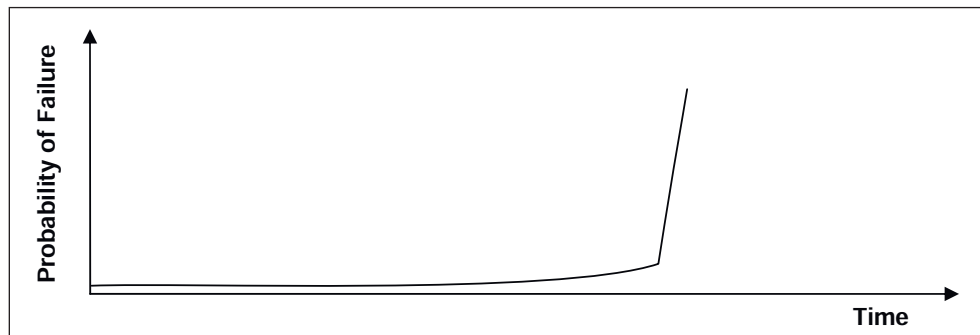


Figure 18.4 – Ideal Failure Profile for Parts.

A drawback of Weibull analysis is the implied assumption that the future is the same as the past. As soon as design, maintenance or operating policies and practices change the prior failure history is unrepresentative of the future. An analysis using the old data to predict the future would be wrong. Weibull Analysis requires complete and accurate failure data over a period of stable practices. The analyst requires thorough understanding of the effects of past and current maintenance and operating policies and practices.

Weibull Analysis is used on failures of the same mode. This is most important. A Weibull plot only applies to one failure mode of an item. It is a false analysis to predict the life of a part that fails for several reasons (e.g. a bearing can have several failure modes – overload, distortion, run short of lubricant, run with water in the lubricant, etc), or for a complex



machine made of many parts. You must plot each part's failure modes separately <sup>76</sup>. Note that in Weibull Analysis a 'part' is defined as a replaceable item. Provided the complete assembly or equipment is replaced at every failure Weibull Analysis can be used. For example, if a mechanical seal, or a drive coupling, or gearbox fails and each is always replaced with a complete assembly, then the mechanical seal, coupling and gearbox are seen as a 'part'. If however the assembly is stripped and the failed parts replaced, and the repaired assembly is then reinstalled, it would not be suitable for Weibull Analysis. A part replaced in the assembly would qualify for analysis, but not the entire rebuilt assembly.

Beware that repeated overhauls of complex equipment result in ever decreasing times between failures after each overhaul. When old parts are reused from one overhaul to the next, the equipment has increasing chance that it will fail sooner than last time. The reused parts are already fatigued and distorted. When used again they fail sooner because prior service stresses reduce their remaining usable life. Having already had a life, they are perhaps close to the end. It is good strategy to identify when equipment parts have accumulated too many service hours of use, or too many overstress cycles, and replace the entire equipment with new <sup>77</sup>.

Weibull Analysis predicts probabilistic safe intervals for operation. It helps in selecting the optimum maintenance type and interval so the cost of spares and downtime are minimised for maximum reliability. With sufficient failure data points Weibull Analysis can advise if Preventive and Predictive Maintenance, or re-design, be investigated to improve a component's reliability. With Weibull Analysis you can compare the cost and estimated effectiveness of your options. You can determine if re-design, or extra quality precautions in assembly, or whether to initiate measures to reduce operational loads and stresses, are the best choice for the business. It applies to deciding warranty periods, shutdown intervals and setting maintenance and inspection intervals. Accurate Weibull Analysis needs trustworthy parts failure data with clear failure modes. With a sophisticated CMMS in use, the collection of failure mode data is more reliable and data analysis can be done electronically.

Many organisations have kept records of failures but not used the data in any useful way. Site failure data is the best source of reliability information available. It is highly relevant and site people can relate their own experience to it. By using your maintenance and parts history you can make failure forecasts, model the benefits of alternative strategies, or analyse the reliability of current systems and their capacity to meet operating needs.

## **Life Cycle Simulation**

Once the Weibull parameters that best fit failure mode behaviours are available they can be used to simulate performance over extended periods. If you have a mathematical model of a part's past you can use the same model to predict its future. Provided the part is treated the same in future as it was in the past, the model is believable. Modern simulation packages involve a Monte Carlo simulation engine that generates random effects in accordance with the historic Weibull parameters over a specified system lifetime. It attempts to mimic what will happen to the part in service if its future were to remain the same as its past. Used in conjunction with FMECA principles, the process of selecting maintenance and inspection intervals becomes a process of playing 'what if' with the Weibull software by comparing the probabilistic effects of different reliability strategies. You then know how to adjust your maintenance to bring the most benefits to the business.

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<sup>76</sup> Sherwin, David., Retired Maintenance and Reliability Professor, 'Introduction to the Uses and Methods of Reliability Engineering with particular reference to Enterprise Asset Management and Maintenance' Presentation, 2007.

<sup>77</sup> Gurgenci, Hal., Zhihqi, Guan, 'Mobile Plant Maintenance and the Duty Metre Concept', Journal of Quality in Maintenance Engineering, Vol 7, No4, 2001.

## Reliability Growth Cause Analysis (RGCA)

Improved reliability has a cause. Just like a failure has a cause, so too is there a cause for improved reliability. You can wait for a failure to happen and then learn from the experience and change your processes to prevent it. That is root cause failure analysis. But it is not proactive behaviour. Such an approach quickly buries you in fire-fighting. It helps you fix a few terrible failures, but not the tens of thousands of defects that are waiting to create the next lot of disasters. Permanent reliability growth requires proactive methodologies that identify all potential problems and stops them from starting. This is what is done in high reliability operations – they never allow defects to begin.

The process maps of your business processes, the workflow diagrams of your operating procedures and the bills of materials for your equipment are the foundation documents for improving equipment reliability. They are used respectively to control the business processes, to control human error and to address limitations in materials of construction and parts' health practices.

Reliability Growth Cause Analysis (RGCA) uses team brainstorming to find ways to grow reliability in a business process or equipment part. It looks for what can be done to intentionally reduce stress and remove risk from a situation. A process map is drawn of the process, or work tasks, or for a machine. The map is used to identify every possible way to prevent failure and eliminate defects throughout the life cycle. Box by box of a process, or part number by part number of a bill of materials, every identifiable way to remove and prevent stress, or to improve the working environment, or to eliminate risk to reliability is identified. Details of the causes of reliability are listed in a spreadsheet, along with the required information about failure and its prevention. Table 18.1 shows the requirements. Together the team identify the strategies, practices and skills needed in design, manufacturing, procurement, construction, operations, and maintenance to deliver lifetime reliability. A plan is developed to introduce them, including all necessary documents, training and skills development.

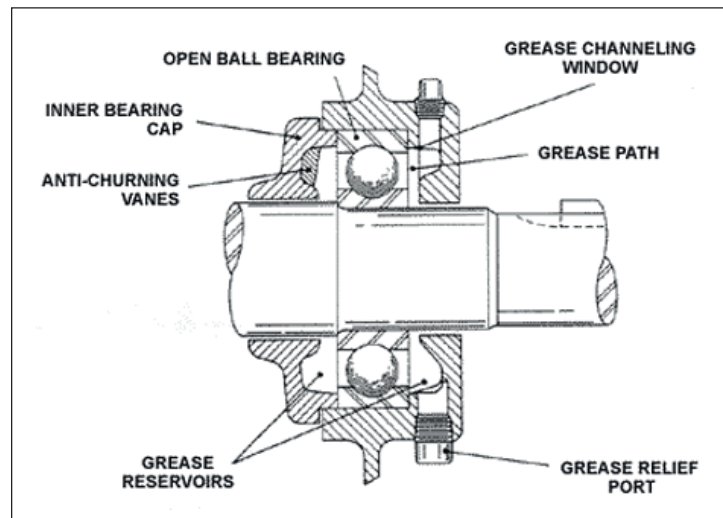
*Table 18.1 – Reliability Growth Cause Analysis Requirements.*

<b>Failure Description:</b> _____
<b>Failure Cause:</b> _____
• Frequency of Cause:
• Time to Repair:
• DAFT Cost:
• Causes of Stress/Overload:
• Causes of Fatigue/Degradation:
• Current Risk Matrix Rating:
• Controls to Prevent Cause:
• Est. failures prevented after risk controls in use (/yr):
• New Risk Matrix Rating:
• DAFT Cost savings from higher reliability:

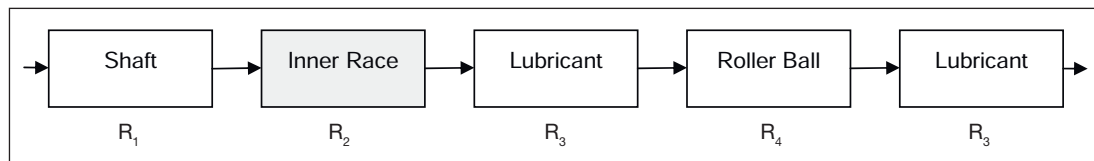
The RGCA method adopts the same strategy for reliability growth as the world-class leaders in industrial safety use for workplace safety improvement. They proactively improve safety by identifying safety risks and installing appropriate protection and improvements against harm

before incidents happen. They don't let hazards that can become accidents even start. RGCA assumes that failures will happen to equipment parts from defects created in engineering, manufacturing, operations, maintenance, installation and procurement processes unless they are intentionally prevented. It requires recognising what can cause risk in all stages of a part's life-cycle and make necessary improvements to prevent every cause starting. Reliability grows by using the right practices and processes that prevent defects and proactively promote health and wellness. RGCA requires you to identify ways that will drive improvement and not simply prevent failure. The aim is to never allow a process step or part to fail so that reliability is maximised. The level of business risk determines which reliability growth improvements will be used and then drives their rapid introduction.

An example of the RGCA methodology is used to maximise the reliability of the inner race of the bearing shown in Figure 18.5. The process map of the shaft and bearing arrangement in Figure 18.6 confirms the configuration is a series arrangement. Hence it is an at-risk assembly and the electric motor would stop should any item in the series fail.



*Figure 18.5 – AC Electric Motor Bearing Arrangement.*



*Figure 18.6 – Process Flow Map for Roller Bearing on Shaft.*

First, a list of known and possible inner race failures is brainstormed by the analysis team. Known inner race failures include a cracked race, a scoured and scratched race, a brinelled and indented race, a loose fitting race, a race suffering electrically arcing, and so on until the team has exhausted all failure modes known to its members. Possible failure modes are then imagined. These include a cracked race intentionally installed and a cracked race unknowingly installed. The next step is to ask of each failure mode how its cause can arise – how can the inner race be cracked? A cracked race can occur from excessive interference fit on the shaft, or a huge impact load, or the shaft is oval and the round race is forced out-of-shape, or a solid piece of material is trapped between the race and shaft during the fitting, or the shaft is heavily burred and the race is forced over the burr and is damaged in the installation process.

Table 18.2 – Example of Reliability Growth Cause Analysis on Inner Race of a Roller Bearing.

<b>Failure Description:</b> Cracked inner roller bearing race		
	<b>Failure Cause 1:</b> Excessive interference fit	<b>Failure Cause 2:</b> Impact to race
Frequency of Cause:	Early Life – 1 per year	Random – 3 per year
Time to Repair:	5 hours	10 hours
DAFT Cost:	\$20,000	\$25,000
Causes of Stress/Overload:	<ul style="list-style-type: none"> <li>• Large shaft</li> <li>• Small bearing race bore</li> </ul>	<ul style="list-style-type: none"> <li>• Abuse when fitting</li> <li>• Start-up with equipment fully loaded</li> </ul>
Causes of Fatigue/Degradation:	Not applicable	<ul style="list-style-type: none"> <li>• Misaligned shafts</li> <li>• Loose race moving on shaft</li> </ul>
Current Risk Matrix Rating:	Medium	Medium
Controls to Prevent Cause:	<ul style="list-style-type: none"> <li>• Update all bearing fitting procedures to measure shaft and bore and confirm correct interference fit at operating temperature and train people annually</li> <li>• Update all machine procurement contracts include quality check of shaft diameters before acceptance of machine for delivery</li> <li>• Update all bearing procurement contracts to include random inspections of tolerances</li> <li>• Update all design and drawing standards to include proof-check of shaft measurements and tolerances on drawings suit operating conditions once bearing is selected</li> </ul>	<ul style="list-style-type: none"> <li>• Update all bearing fitting procedures to include using only approved tools and equipment and train people annually. Purchase necessary equipment, schedule necessary maintenance for equipment</li> <li>• Change operating procedures to remove load from equipment prior restart and train people annually (Alternative: Soft start with ramp-up control if capital available)</li> <li>• Align shafts to procedure and train people annually</li> <li>• Update bearing fitting procedures to measure shaft and bore and confirm correct interference fit at operating temperature and train people annually</li> </ul>
Est. failures prevented after risk controls in use (/yr):	All future failures	80% of future failures
New Risk Matrix Rating:	Low	Low
DAFT Cost savings from higher reliability:	\$20,000 per year	\$60,000 per year

For the first cause noted of a cracked inner race – excessive interference fit – the team asks, “How is excessive shaft interference prevented?” This problem is one of incorrect tolerances between race and shaft. It is usually a manufacturing error of the shaft or the race. The team is now required to develop proactive measures to ensure a race is never fitted to an incorrectly made shaft, or an incorrectly made race is never fitted to a good shaft. One prevention is to micrometer the shaft and the race and check the fit matches the bearing manufacturer’s requirements for the model of bearing. Additional prevention is to confirm the model of bearing is correct for the service duty and operating temperatures. These checks become a procedural requirement written into the applicable ACE 3T procedures. But the team is charged with finding all cause of reliability and much more can be done earlier in the life cycle to prevent this failure. These additional early life cycle preventive measures are listed in Table 18.2.

The team then continues with the next cause of how an inner race can be cracked – heavy impact – and develops preventive actions (heavy impacts can occur when a race is fitted to a shaft with hammer blows or overloaded in a press, or a loose race on the shaft rattles from side to side, or a badly aligned shaft causes the race to be cyclically loaded, or it suffers a huge start-up overload). The process continues for a shaft that is oval, for a solid piece of material

trapped between race and shaft during the fitting, for a heavily burred shaft, and so on. With each preventive measure put into place, and made standard practice through using ACE 3T procedures and workforce training, each part's reliability grows.

Every RGCA performed applies to every similar situation, and the learning from one analysis is transferred to every other similar situation by updating all other applicable procedures. In this way RGCA applies Series Reliability Property 3 and rapidly improves every other like circumstance.

### Measuring Reliability Growth

If your reliability improvement efforts are working the evidence will be a reduction in the number of equipment failures. There are several ways to detect the change.

### Time Series Plots

By measuring the time between failures you can see if the period is increasing (reliability is improving), decreasing (reliability is worsening) or unchanged. Figure 18.7 shows how improving equipment reliability would look on a 'time between failures' plot for an item of equipment.

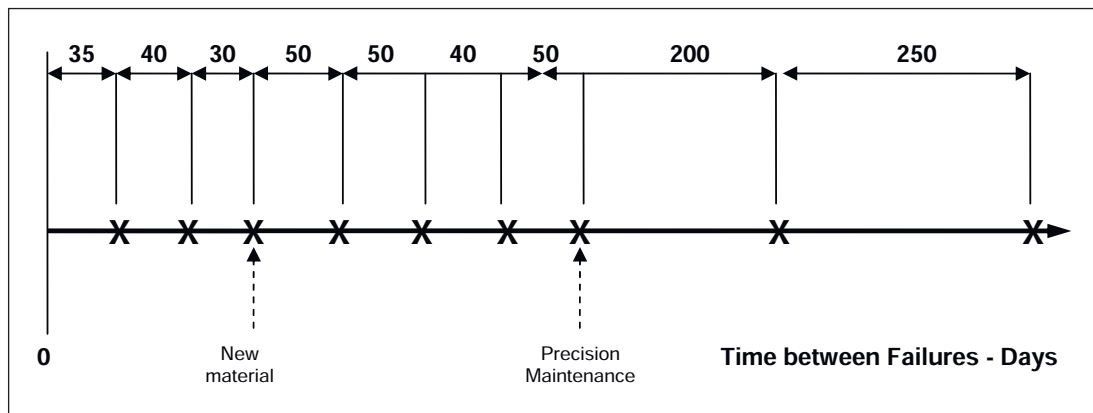


Figure 18.7 – Time Series Plot Showing Increasing Time between Failures for a Component.

The 'X' on the timeline represents the failure of a part or assembly that causes the equipment to fail. There may be a variety of parts in an item of equipment that can fail and a variety of ways to fail each part. The time series above simply reflects when the equipment failed. If correct information on each failure mode was available, a time series by failure mode could be developed. The time series plot clearly shows that from a history of frequent failures every 30 to 40 days, the days between failures have increased – the part is lasting longer and longer. The time series plot represents reliability growth and the effect of changes on the health and wellness of the machine.

The mean time between failures (MTBF) in the early life period was:

$$\text{MTBF} = \frac{35 + 40 + 35}{3} = 37 \text{ days}$$

Following the material change, it became:

$$\text{MTBF} = \frac{50 + 50 + 40 + 50}{4} = 47 \text{ days}$$

After the introduction of Precision Maintenance, it became:

$$\text{MTBF} = \frac{200 + 250}{2} = 225 \text{ days}$$

### Duane/Crow-AMSAA Plots

Another way to see reliability growth is by plotting the observed number of cumulative failures against cumulative time on logarithmic paper. Such a diagram is known as a Duane reliability growth plot and applies for a piece of equipment, a complete production process and even to an organisation. The development of log-log reliability growth plots can be traced back to the 1930s investigations of the learning curve for building airplanes <sup>78</sup>. It was developed into a graphical method in the 1960s by James Duane while working at General Electric for use in predicting reliability improvements of new product developments. In the 1970s a mathematical derivation was developed by Larry Crow while in the employ of US Army Material Systems Analysis Activity (AMSAA). The measurement of reliability growth reflects changes in system reliability caused by changed efforts to affect reliability.

The method is now used in industry as a historic reliability key performance indicator, as well as a means to predict the future impact of reliability improvement initiatives. The technique is purely empirical, but has been a very good approximation when applied to complete machines suffering multiple failure modes <sup>79</sup>. Duane/Crow-AMSAA plots are power laws that measure failure rates. They imply a relationship between the failure of equipment and the chance of failure it carries.

A Duane plot starts by creating a table like Table 18.3, which in this case lists the failure dates for the time series plot of Figure 18.7 and the cumulative days between failures. On a computerised log-log plot, like that in Figure 18.8, or in 1:1 scale on a sheet of log-log paper, like Figure 18.9, a graph is drawn of the cumulative days verses the cumulative failures.

*Table 18.3 – Reliability Growth Cumulative Days.*

Failure No	Failure Date	Cumulative Time in Days	Comments
0	January 25 <sup>th</sup>		New equipment installed
1	March 1 <sup>st</sup>	35	
2	April 9 <sup>th</sup>	75	
3	May 9 <sup>th</sup>	105	New material selected
4	June 30 <sup>th</sup>	155	
5	August 21 <sup>st</sup>	205	
6	October 5 <sup>th</sup>	245	
7	November 26 <sup>th</sup>	295	Precision Maintenance introduced
8	July 1 <sup>st</sup>	495	
9	March 26 <sup>th</sup>	745	

In the log-log plot of Figure 18.8 there are three identifiable regions – one reflecting the period of the first three failures, another following the material change and the third following the introduction of precision maintenance. The change of material made a small improvement. You can tell that from the changed slope of the line in that portion of the graph. The slope after the material change is shallower than before the change. The fact the line is straight implies that the failure rate was relatively constant and the small reduction in slope indicates there was slight

<sup>78</sup> Comerford, Nigel, 'Crow/AMSAA Reliability Growth Plots and their use in Interpreting Meridian Energy Ltd's, Main Unit Failure Data', Areva T&D, New Zealand, 2005.

<sup>79</sup> Sherwin, David, Retired Professor of Maintenance and Reliability, 'Introduction to the Methods of Reliability Engineering with particular emphasis to Engineering Asset Management and Maintenance' presentation, 2007.

improvement on its earlier life. You can also confirm those observations on the time series plot of Figure 18.7 where the change of material improved the Mean Time Between Failure from 37 days to 47 days. The big improvement came with introduction of precision maintenance when MTBF jumped to 225 days. The slope in Figure 18.8 shows this great improvement.

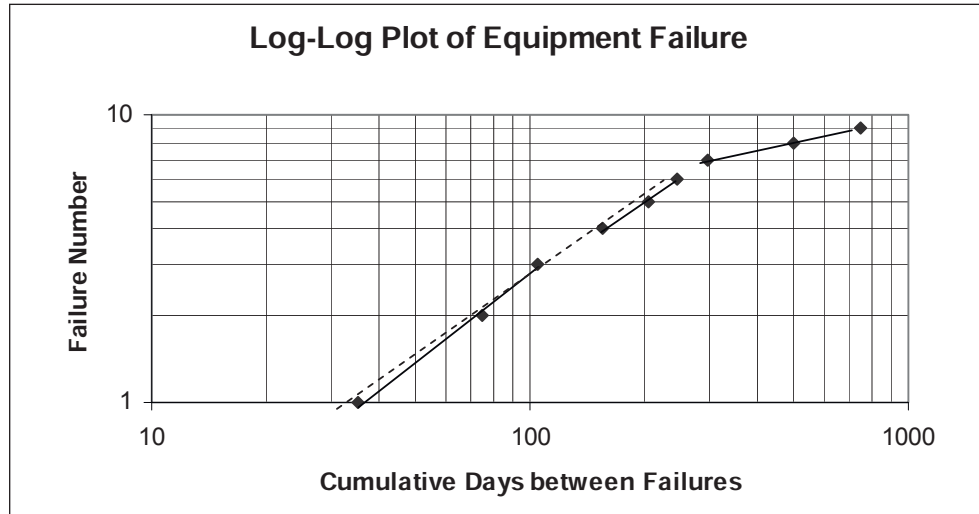


Figure 18.8 – Duane Log-Log Plot of Equipment Reliability.

Notice the triangles drawn on Figure 18.9 have the same slope as the lines. Because the graphical log-log plot is 1:1, you can measure the X and Y lengths with a ruler and calculate the slopes. The slopes tell a lot about what is happening with the equipment. The slope is called the Beta Value – ' $\beta$ ' (not to be confused with the beta used in Weibull Analysis; the two have very different meanings). The Beta is a reliability trend indicator.

- Beta < 1,  
Reliability Improving
- Beta ~ 1,  
Reliability Static
- Beta > 1,  
Reliability Deteriorating

In Figure 18.9, you can see that the beta for the early failures was indicating a steady reliability trend. After the material change, the reliability was better. With the introduction of precision maintenance the reliability trend improved massively.

Software for Crow-AMSAA investigation and reliability improvement analysis is commercially available and provides useful management indicators when sufficient data points be available.



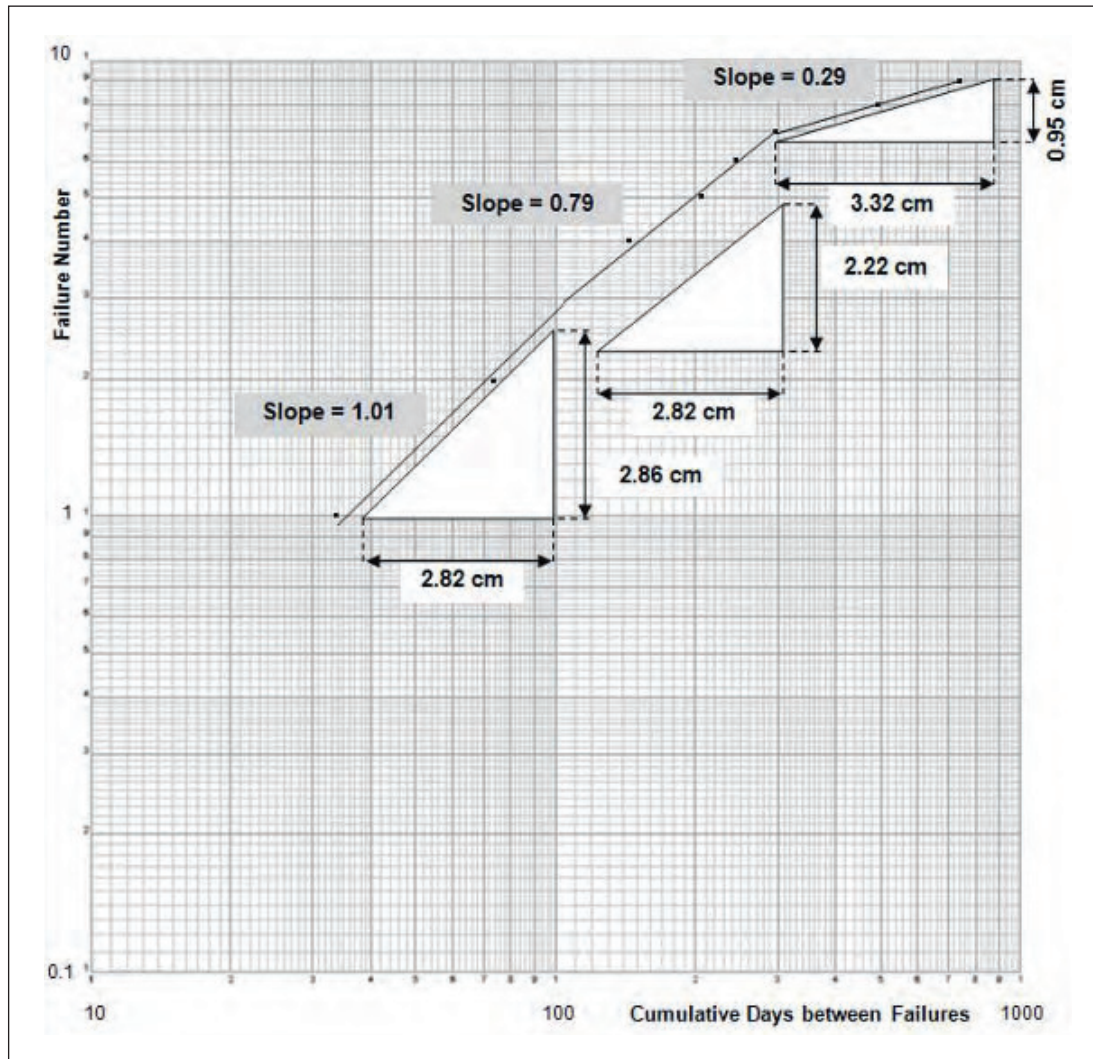
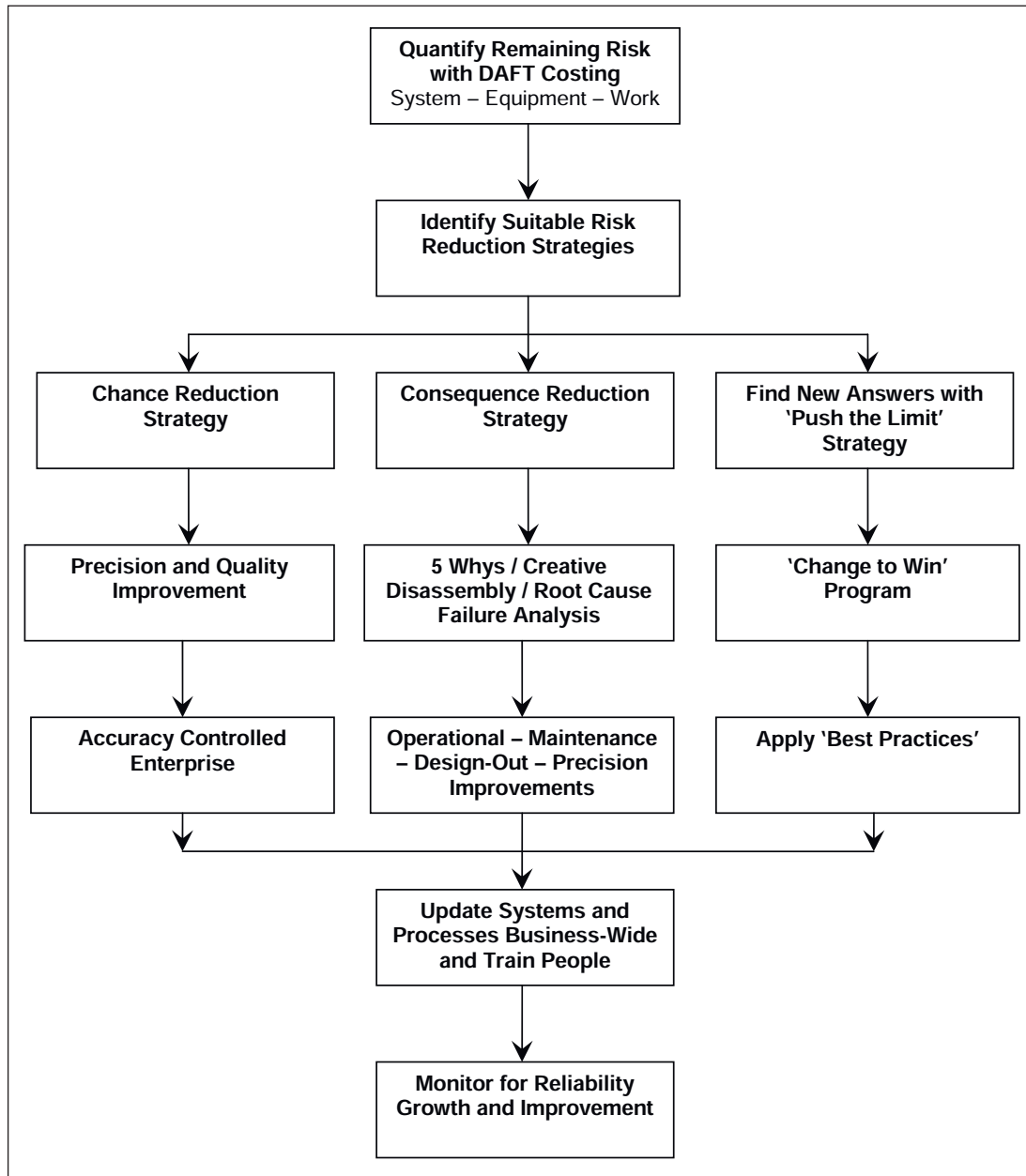


Figure 18.9 – 1:1 Scale Log-Log Paper Plot of Equipment Reliability.



# PROCESS 6 – Operating Risk Continual Improvement



## **Description of Process 6 – Operating Risk Continual Improvement**

### **Description of Process 6 – Continual Improvement**

The war against risk never stops. No improvement secured must ever be lost. No new risks must ever enter your operation. Work on reducing and removing all operating risks remaining.

### **Quantify and Prioritise Remaining Risk:**

Assess the risks remaining in your operation by using DAFT Costing to measure the potential business-wide losses from equipment failures. Use double-Pareto charting to prioritise and focus your failure reduction efforts to get maximum returns.

### **Identify Suitable Risk Reduction Strategies:**

Reduce the chance of risk on your targeted high priorities. Use the Reliability Growth Cause Analysis (RGCA) method to spot new opportunities for reliability improvements.

### **‘Change to Win’ Program:**

To get permanent changes in your operation you will need the support and commitment of the people there. The ‘Change To Win’ program is a process to involve people in making permanent improvements in how they work and what they do to lift reliability.

### **Apply ‘Best Practices’:**

To get world-class performance, use world-class practices. Better results need better standards and better practices. Find them and bring them into the operation. Make them the ‘way we do things around here’. Don’t wait for problems to justify improvement; make improvements so that there won’t be any problems.

### **Update Systems and Processes Business-Wide:**

To make good change permanent, include it into all documents and business processes. Imbed it in the work processes and make necessary information easily available to everyone. Use your business systems to trap world-class practices in the business so they are used always and never lost. Train and retrain your people to the best practices.

### **Monitor for Reliability Growth:**

Use Key Performance Indicators and Reliability Growth Plots to track the direction and progress made. Address and improve those activities not yet performing well enough.

## 19. Failure Root Cause Removal

Highly reliable organisations do not accept things going wrong. They proactively focus on preventing problems entering their operation and find, then fix, those that remain. They set control mechanisms, standards and checkpoints in place to spot and stop the defects that turn into future failures. They look for what can go wrong before it does and prevent it happening. They learn from their problems and proactively act to prevent them. If your operation is having equipment and production problems, you need to discover what they are and how to solve them! To solve problems fast you need to draw together relevant information and knowledge. The vast majority of production problems are the same ones repeated by different people in different plants at different times. You should only need to solve a problem once. Let everyone else in your business use the answer and get any new training they need. This puts Series Reliability Property 3 to work for you and you get reliability growth across the business and not just in one machine.

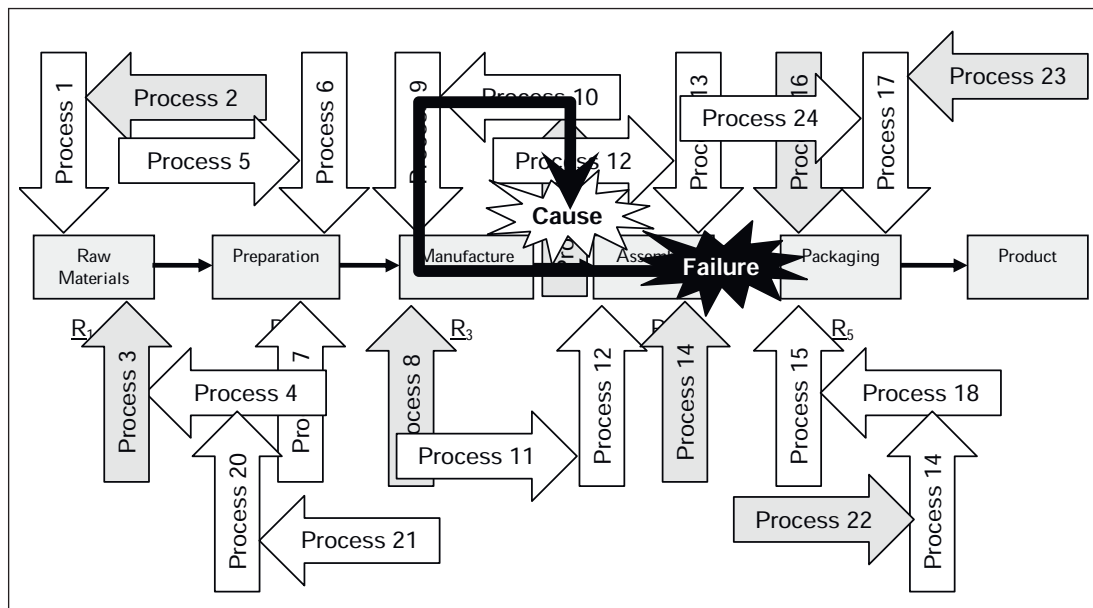


Figure 19.1 – Failures Occur throughout the Process Chain.

If your industrial maintenance management practices and asset management processes do not deliver sustained high production performance, there are underlying root causes which need addressing. Nothing happens by accident. Most often production equipment problems and failures are only symptoms of the real causes. The real causes are hiding deep within an operation's processes and habits. Until you solve the underlying issues that produce the failures they will continue to happen. Determining the real problem is finding the root cause. There are special techniques for determining the root cause of a problem. One technique used for procedural failures is the '5 Whys'. For equipment failures Root Cause Failure Analysis is often favoured. For the tens of thousands of defects in your plant and equipment waiting to become failures, we use creative disassembly to fix them <sup>80</sup>.

World-class operations recognise the interconnectivity of their processes and work hard to ensure right results at every stage, in every process. Figure 19.1 shows a failure in product assembly. The root cause traces back to manufacture, where it leaves the process and enters another, then a second and a third. The defective item started its life elsewhere and ended up

<sup>80</sup> Brown, Peter, Wishaw, Max, 'Precision Maintenance for Engineers' Course, Industrial Training Associates, Perth, Australia, 2000.

causing problems in Assembly. There are innumerable opportunities for errors and defects to occur in all processes. Process after process connects with others such that a tangled web of interaction occurs around and along every process. Errors, mistakes, and defects can come from everywhere. Any process that goes wrong impacts on numerous others downstream of it. Much time, money and resources will be wasted. The problem needs to be fixed. That will take more time, money and resources. If you want an operation where good results are natural and excellence abounds – ensure your processes allow no defects to enter your business.

### **Creative Disassembly and Defect Removal**

Creative disassembly is part of precision maintenance where machines and equipment are built to the quality standards that ensure defects are removed and failures never happen. The method requires identification of flaws with machinery and their immediate correction. It operates at the equipment parts level and strikes at the heart of the thousands of defects making-up the base of the equipment failure pyramid. By reducing the number of defects in machinery fewer opportunities present themselves for catastrophic failures. The plant operator and maintenance technician become the root cause analysts for their operating plant and equipment. Instead of operators only running the plant and the maintainer only replacing parts and doing maintenance, they are trained to find the reason for a failure and correct its root cause. They are given authority to follow-through and do all necessary work, including scheduling production outages to do the precision maintenance needed to prevent repetition of the problem.

There are three phases to creative disassembly analysis – pre-shut-down, pre-strip-down and strip-down. During the work comparisons are made against specified ACE 3T precision standards. When defects are detected they are removed or corrected, and the equipment is returned to the applicable precision standard when re-built.

#### **1. Pre-shut-down data collection**

- a. Records from the CMMS, parts usage, repetitive maintenance and operating problems
- b. Condition monitoring data such as vibration and bearing characteristics, thermography, oil analysis, etc
- c. Checks for running softfoot and machine distortion while operating; identify resonance problems and poor supporting and hold-down structures.

#### **2. At shut-down, but prior strip-down, take measurements and detailed observations**

- a. Where thermal growth occurs collect the hot growth and alignment readings
- b. Identify witness marks showing relative movement between parts
- c. Notice presence of unusually deposits from wearing parts like drive belts and couplings
- d. Take lubricant samples for analysis and patch testing of wear particle count while still hot
- e. Check for static softfoot distortion problems.

#### **3. Strip-down measurements and investigative observations**

- a. Look for witness marks and tell-tale evidence of incorrect operation and behaviours
- b. Mark relative positions of bearings to later confirm correct location
- c. Inspect bearing wear patterns for evidence of spalling and other failure modes
- d. Incorrect roller or race motion, cage damage, fretting corrosion, out-of-roundness, shaft straightness, etc
- e. Inspect for damage and wear patterns on moving parts such as gear teeth, pulleys, belts, etc.

Take time to do the job of creative disassembly and precision rebuilding well. It leads to world class equipment performance as more and more defects are removed from your plant and machinery.

## Root Cause Failure Analysis

Root Cause Failure Analysis (RCFA) tracks problems down to their roots to identify the necessary changes that would stop the problems reoccurring. Whether a breakdown of a piece of equipment, an industrial accident, or the failure of a business plan, root cause failure analysis will help to identify the reasons for the incident. It provides the necessary depth of analysis to find the causes and then develop useful changes to remove them from the operation. The effectiveness of RCFA in solving production problems and improving production performance is well proven. Root Cause Failure Analysis solves both common cause failures and special cause problems. As each RCFA improvement project is successfully completed the plant reliability and productivity rise higher and higher. Figure 19.2 shows how to use RCFA to improve operating performance.

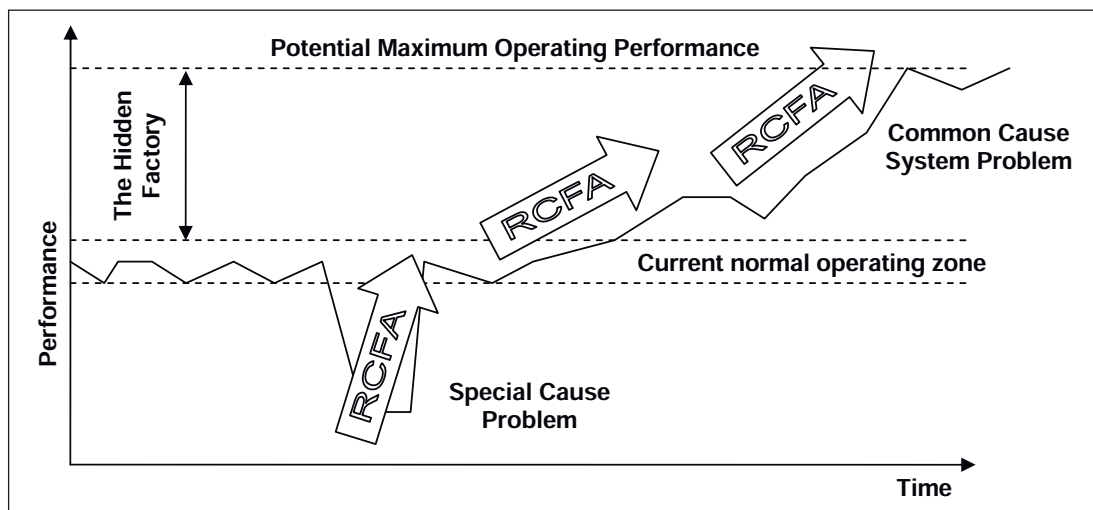


Figure 19.2 – Use of RCFA to Correct Common and Special Cause Problems.

Many companies train their key people on Root Cause Failure Analysis. It starts life with a rush and then dies from insufficient time and resources. RCFA is a powerful concept when used all the time. As an enabling tool for problem solving it is best used continuously ‘on the shopfloor’. If reserved for investigating major failures by engineers and managers, then use of RCFA will die-off quickly. Saving RCFA for major failures guarantees that major failures will continue because it is not used to solve the small problems that grow into major failures<sup>81</sup>. To remove catastrophes you must remove the tens of thousands of chances for defects to align with opportunity and progress to failure. Make RCFA live every day where the risks reside – in your processes and on the shopfloor!

A formal RCFA course will teach you the technique of using Fault Tree Analysis (FTA) to find root causes and to build successful methods to prevent them repeating. During the course you spend a great amount of time understanding and practicing RCFA so that you are comfortable to use it. A good RCFA course has a hands-on, practical focus intended to help Attendees understand where equipment failure causes come from and how to find and remove

<sup>81</sup> Nelms, Robert C, ‘The Latent Causes of Industrial Failure ....How to Identify Them, and What to Do about Them’, Failsafe Network, Inc. Montebello, VA, USA.



them. The method brings a team of 3 to 6 knowledgeable people together to investigate the problem using evidence left behind from the failure. Deciding the composition of the team is more about including all the skills and knowledge needed to find the cause and solve the problem, than getting a certain number of people into the team. The team brainstorms to find the many causes of a fault. The solution selected must prevent the problem recurring.

Improving existing plant performance requires the elimination of repeat failures. RCFA is a search for the ‘root cause’ of the problem. Effective RCFA is about seeking simple solutions that control the causes of problems. Like a detective, we look for causes from the effects and evidence and trace them back to the first cause. The process starts by defining a problem and identifying all possible causes. We ask, “How can the effect arise?”, and answer with a cause or combination of causes. Each cause is then taken as an effect and we continue to ask how that one arose. With this method of questioning a cause and effect chain is established. During analysis a fault tree, as in Figure 19.3, is developed. Starting with the failure it is progressively traced back to each cause that could have led to the previous cause. This continues until each trail can be traced back no further. Each result of a cause must clearly flow from the one before it. If it is clear that a step is missing between causes, it is added in and evidence is required to support its presence. Using what evidence remained after the fault, as well as discussions with people involved in the incident, all the non-contributing causes are removed and the contributing causes are retained. Once the fault tree is completed and checked for logical flow the team then determines what changes to make to prevent the sequence of causes and consequences from again occurring.

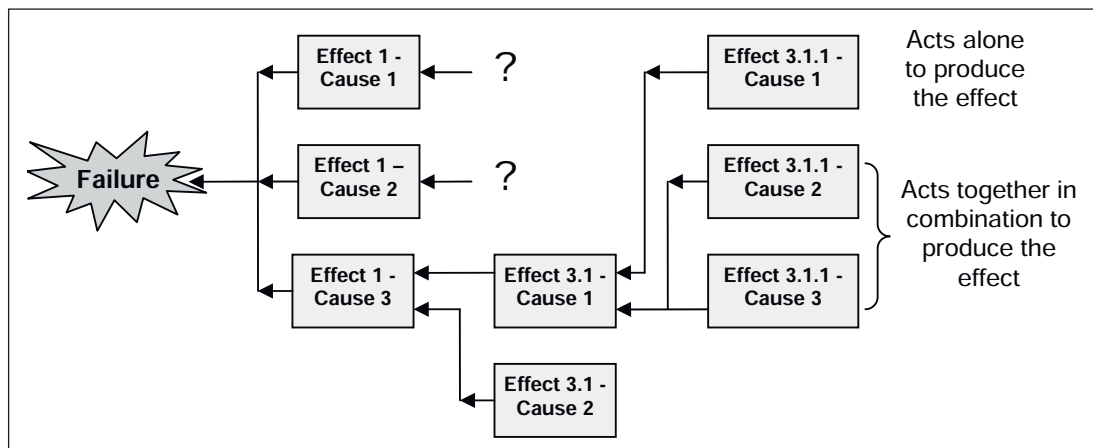


Figure 19.3 – Root Cause Failure Fault Tree.

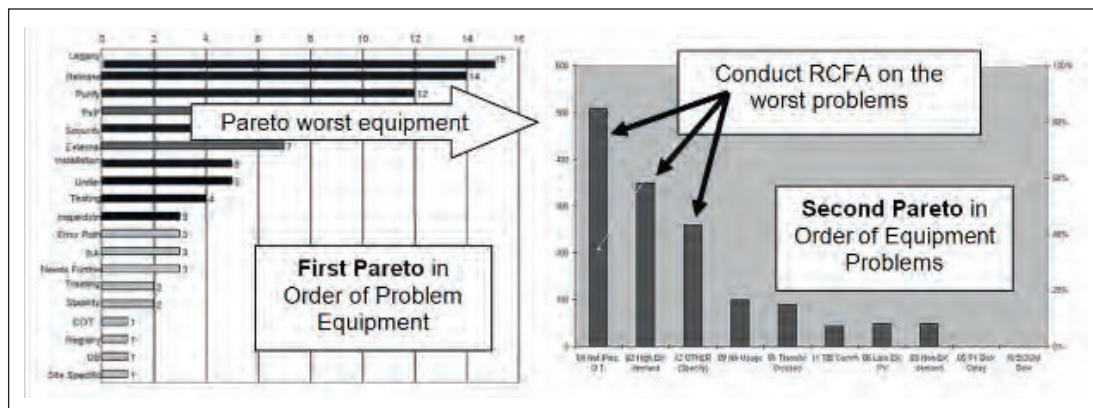


Figure 19.4 – Double Pareto Chart Method used to Identify Equipment and Problem Priorities.

When RCFA is used to address common cause problems you first select the least reliable equipment for improvement and solve its problems, then do the next worst equipment, and so on. By fixing the worst equipment you improve reliability using the Series System Property 1 – ‘The reliability of a series system is no more reliable than its least reliable component’. You work your way through the least reliable equipment in your operation one after the other, gradually improving the whole system reliability. The approach starts by producing a Pareto chart of the ‘bad actors’ equipment in an operating plant. Equipment across the operation is charted in order of DAFT Cost impact. The worst performing equipment items are then identified on the chart. The second step is to make another Pareto chart for each of the worst equipment showing the DAFT Cost of each problem on that equipment. Finally RCFA is applied to address the causes. Figure 19.4 is an example of the double Pareto approach.

World class companies take the learning from an RCFA and apply it throughout their business. They use Series System Reliability Property 3 with what they learn and fix every other similar problem. They know that what went wrong with one machine is a symptom of their business processes, and it can happen again. With each RCFA they improve their entire business.

### Preventing Reoccurrence of the Failure

It is not necessary to remove the root cause to prevent the failure. The failure can be prevented by breaking the chain of events anywhere along the fault tree. But a defect not removed remains behind to restart the same failure sequence, and perhaps hundreds of other failure sequences as well. Often the fault tree leads to an initial design problem. In such a case redesign maybe necessary. Where the fault tree leads back to a failure of procedures it is necessary to fix the procedural weakness, or to install a method to protect against the consequence of the procedural failure. It includes doing all necessary training. Figure 19.5 is a sample fault tree for the moral story of the kingdom lost because of a missing horseshoe nail. The story goes that before an important battle a king sent his horse to the blacksmith for shoeing. He was one nail short for the king’s horse, as he had shoed all the knight’s horses for battle. The groomsmen told the blacksmith to do as well as he could. The blacksmith warned him that the missing nail might allow the shoe to come off. The following day the King rode into battle not knowing of the missing horseshoe nail. In the midst of the battle he rode toward the enemy. As he approached them the horseshoe came off the horse’s hoof causing the horse to stumble and the King to fall to the ground. The enemy saw the King fall and was quickly onto him and killed him. The king’s troops seeing the death gave up the fight and retreated. The enemy surged onto the city and captured the kingdom. The kingdom was lost all because of a missing horseshoe nail.

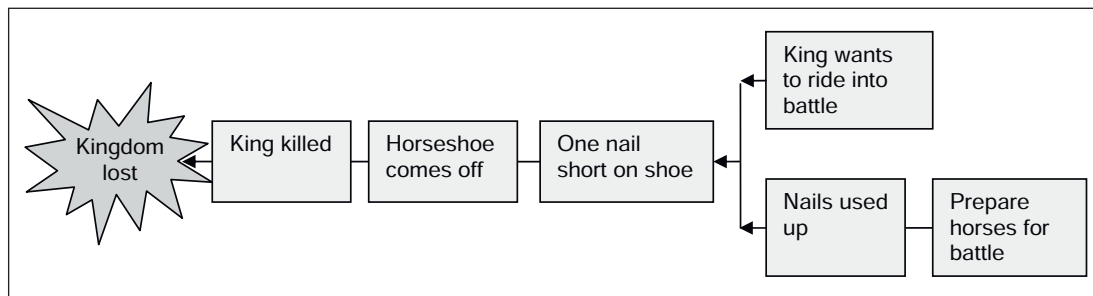


Figure 19.5 – RCFA Fault Tree for the Missing Horseshoe Nail Story.

The Fault Tree explains step-by-step how the events leading to the king's death unfolded. Notice that two separate event 'branches' had to occur together for the sequence to continue to the fateful end. Prevent any of the causes and the kingdom could have been safe.

In our story the next king chances the same death if he does not fix what killed the previous king. It is critical to all future kings that they know how a missing horseshoe nail can kill them. Don't keep what is learnt in an RCFA secret – tell everyone; improve your processes company-wide with the learning; get the knowledge out and into use quickly. Use Series Reliability Property 3 and everyone gains a lot from a small amount of effort. There is one more question for you to consider – should the blacksmith be drawn and quartered? Was it his fault that the king died, or was it a process fault that he ran out of nails?

### **The 5-Whys – Creating Why Trees**

The '5-Whys' is a simple way to try solving a procedure problem without a large detailed investigation requiring many resources. It is a simple form of root cause analysis<sup>82</sup>. It is used to explore the real cause of a problem or situation. Most obvious explanations have more underlying problems. By repeatedly asking the question, 'Why?' you peel away layers of symptoms that can lead to the root cause. The 5-Whys help to determine the relationships in a problem. It is one of the simplest investigation tools easily completed without statistical analysis. When problems involve human factors this approach is easiest because it is less stressful. Start with a statement of the situation and ask why it is happening. Then you ask 'Why?' of the answer to the first question, and so on. The question 'Why?' is asked five times. By refusing to be satisfied with the first explanation you increase the possibility of finding the true root cause of a situation. Although this technique is called '5 Whys', five is a rule of thumb. You may need to ask the question fewer, or more times, before you find the root of a problem (there is even school of thought that seven 'whys' is better; that five 'whys' is not sufficient to uncover the real truth).

A '5 Whys' Questionnaire Form is used to record the analysis. Just like an RCFA, a team of people competent and knowledgeable in the problem are used to brainstorm the situation. After describing the problem the team develops a cause and effect tree relationship back to the root cause using the 5-Why method. The consensus response to each question is written in the appropriate space on the form. Once the trail to the root cause is found the team is asked to use the available evidence to prove each answer would really cause the previous one. The 3W2H set of questions is used to help confirm the right cause from all those possible. If an answer does not satisfy the evidence, the team identify what is missing and correct the answer. The team continues confirming the veracity of each cause-effect connection against the evidence until all connections are confirmed.

### **The 3W2H set of Questions**

To gain insight into an event you need to ask poignant questions that verify what really happened to cause the incident. If the problem is to be solved its real causes must be known with certainty. Otherwise the proposed solution may not work because it does not stop the true cause-effect path. The 3W2H acronym is a useful device to help remember the questions to ask. For each cause-effect connection answer the 3W2H questions to draw-out details of the cause-effect relationship. There must be real evidence that each answer is the right one for the question asked.

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<sup>82</sup> Some contents for this topic are from the website <http://www.isixsigma.com/library>.

- With what – *the physical evidence of what happened*
- When – *the exact time in the process chain*
- Where – *the exact point in the process chain and physical location in the facility*
- How – *the actual activity and actions being performed prior the incident*
- How much – *the engineering specifics of the activity, e.g. height, weight, speed, colour,...*

### Completing a 5-Why Questionnaire Form

Use a one-page form like the example in Table 19.1 to record the questions, answers and evidence.

1. Write down and describe the specific problem to formalize and clarify it. It helps the team members to focus on the problem.
2. Calculate the DAFT Cost impact of the problem on the whole operation.
3. Ask ‘Why’ the problem happened and write the answer below the problem.
4. If the answer provided does not identify the root cause of the problem that you wrote, ask ‘Why’ again and write that answer down.
5. Continue asking ‘Why’ until the team agrees it has identified the problem’s root cause.
6. Confirm each answer with the evidence. If the evidence does not support the answer seek an answer that fits the evidence.
7. Identify solutions that will break the cause-effect chain.
8. Implement the simplest solution.

The estimated DAFT Cost is the ‘Defect and Failure Total Cost’ and is the total organisation-wide cost of the failure. Identify every dollar lost across the whole organisation. It will make implementation of a solution easier for management to accept if you have a strong business case.

The example in Table 19.1 is the analysis of a failure to get to work on time. As you can see, the Five Whys lead the team to the root cause of being late to work – losing all the money in a poker match (but it is not the real cause of the person’s problem). To prevent the car running out of gas he needed money to buy fuel. The simple solution to the problem is to carry a credit card, rather than to teach the person to ‘bluff’ a hand. There is no need to solve the last cause to fix the problem.

Notice the comment regarding ‘Latent Issues’. The honest, true cause of the problem was being unable to control ones money. Latent issues are the underlying beliefs and values that make us act as we do. These beliefs and values encourage our behaviours along certain paths. They are the habits we have adopted and now no longer question. Many of these habits do not lead us to good results. The ‘5 Why’ table includes the question of latent issues so we are forced to see our true selves, and not think that because a problem is prevented it cannot happen again. It will happen again, in some way or another, if we do not change our beliefs and values.

Progress and development is an evolutionary process not a revolutionary process. Those companies that evolve fastest are more successful than those that wait for change to be

imposed on them. If you want rapid evolution in your operation help the people there to develop problem solving skills and knowledge. Give those with the problems the tools they need to team-up and find the solutions for themselves.

*Table 19.1 – A 5-Why Analysis Form.*

<b>Why Tree Questionnaire Form</b>			
<b>Team Members:</b>		<b>Date:</b>	
<b>Problem Statement:</b> On the way to work your car stopped in the middle of the road.			
<b>Estimated DAFT Cost:</b> Taxi fare x 2 = \$50, Lost 4 hours pay = \$100. Plus big stress caused at home and at work!			
<b>Recommended Solution:</b> Carry a credit card to access money when needed.			
<b>Latent Issues:</b> Gambling away all the money shows a lack of personal control and responsibility of money.			
<b>Why Questions</b>	<b>3W2H Answers</b> (with what, when, where, how, and how much)	<b>Evidence</b>	<b>Solution</b>
<b>1. Why</b> did the car stop?	Because it ran out of gas in a back street on the way to work	Car stopped and standing at side of road	
<b>2. Why</b> did gas run?	Because I didn't put any gas into the car on my way to work this morning.	Fuel gauge showed empty	
<b>3. Why</b> didn't you buy gas this morning?	Because I didn't have any money on me to buy petrol.	Wallet is empty of money	Keep a credit card in the wallet
<b>4. Why</b> didn't you have any money?	Because last night I lost it in a poker game, I played with friends at my buddy's house.	Poker game is held every Tuesday night	Stop going to the game
<b>5. Why</b> did you lose your money in last night's poker game?	Because I am not good at 'bluffing' when I don't have a good poker hand and the other players jack-up the bets.	Have lost money in many other poker games	Become better at 'bluffing'
<b>6.</b>			
<b>7.</b>			

## 20. Precision Maintenance Skills and Standards

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 low stresses 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 far fewer breakdowns
- 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. Realising 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 precision in your operation.

### Financial and Operating Benefits of Precision Maintenance

The two graphs in Figure 20.1 tell a remarkable story – when machine vibration levels fall, so do the maintenance costs; dramatically at first, then gradually and continually as use of precision practices improves. That means machinery does not breakdown. It runs brilliantly for longer and plant availability, throughput and utilisation are at their maximum. As a consequence there is more time to make more product at less cost to sell for more profit using fewer people.

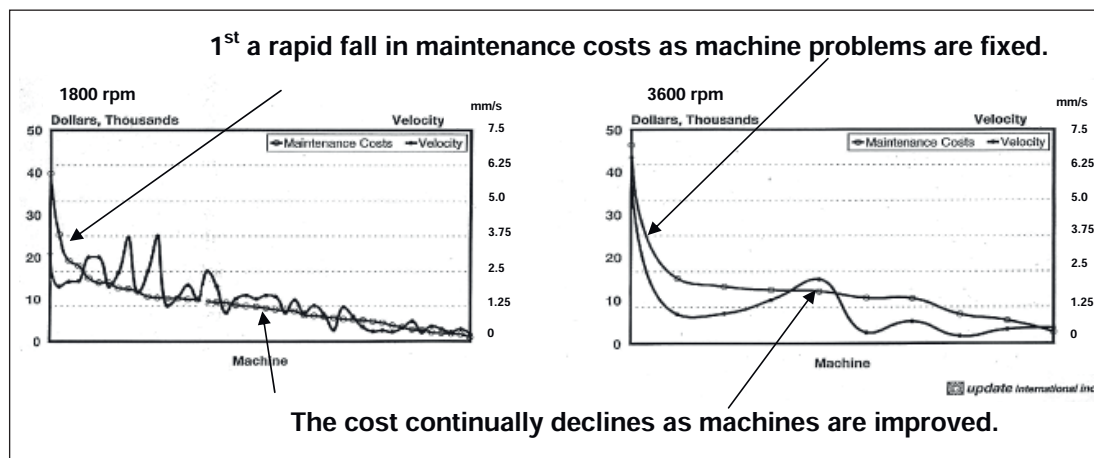


Figure 20.1 – Maintenance Costs Fall When Overall Machine Vibration Levels Fall.

<sup>83</sup> Buscarello, Ralph T., Update International, Lakewood, Colorado, USA, 1993.



Table 20.1 shows results of a machine vibration survey in a large industrial facility. It records bearing vibration levels taken while operating the equipment, along with their previous year's maintenance costs. Low bearing vibration is 1mm/s to 2 mm/s, at 8 mm/s a machine is running very rough. The costs for equipment with low vibration are 70% – 80% less than for machines that ran rough. When equipment is built to fine standards that prevent distortion and provide healthy internal conditions it runs smoother and its parts suffer substantially less stress and fatigue.

*Table 20.1 – Machine Vibration to Maintenance Cost.*

Machine Type	Highest Velocity mm/s	Dollars Spent Last Year	Lowest Velocity mm/s	Dollars Spent Last Year	Savings with Precision
Single Stage Pumps	5.6	\$3,200	2.0	\$650	80%
Multi Stage Pumps	4.8	\$6,100	1.5	\$1,100	82%
Major Fans & Blowers	9.0	\$900	2.8	0	100%
Single Stage Turbines	3.8	\$8,200	1.0	\$2,000	76%
Other Machines	7.8	\$11,850	3.0	\$3,700	69%

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.

The list below are the thirteen requirements for a precision maintenance program:

1. Accurate fits and tolerance at operating temperature
2. Impeccably clean, contaminant-free lubricant life-long
3. Distortion-free equipment its entire life
4. Forces and loads into rigid mounts and supports
5. Laser accurate alignment of shafts at operating temperature
6. High quality balancing of rotating parts
7. Low total machine vibration
8. Correct tensions in all fasteners
9. Correct tools and test equipment in the condition to do the task precisely
10. Only in-specification parts are installed
11. Creative disassembly to find and remove defects and failure causes
12. Proof-test that precision is achieved
13. A business process to consistently apply the requirements in a successful way.

There is nothing in the list that should not already be standard practice in every industrial operation. But it hardly ever happens. The reason is the exacting standards required to deliver the excellent equipment health that delivers failure-free operation are not specified in company



quality systems. They are not taught to engineers, nor to operators and maintainers, and are not important to those supervising work quality. So everyone works to their own level of misunderstanding, which leads to variation, confusion and inaccuracy. Defects are thereby created all the time that cause operating problems and equipment failures. It is as predictable as night following day. But it does not need to be that way. It 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, gearboxes – 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.

These standards are measurable, they define the ‘engineering numbers’ that are proof of compliance to the standard. Standards are needed for 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 and the test to use
- 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 requires 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 that 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 will prevent that.

## Starting a Precision Maintenance Program

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. Those that do not know the right answer, and have no way to find it, will guess. If that happens then chance and luck take over 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 may 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. It 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 reducing fastener problems. Using a process that delivers  $\pm 25\%$  variation when you need  $\pm 10\%$  variation depends on luck for its 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 practices. With ACE in place you have the tool to drive amazing equipment reliability and production results. You solve equipment performance problems forever. More importantly, it lets you make Precision Maintenance a habit throughout your operation. 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 operational 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.

### Setting Precision Quality Standards for Your Equipment

The solution to equipment reliability problems starts when the management of a business set standards and promote them, train to them and enforce them. The standards you need already exist, and have existed for decades. Your challenge is to bring them alive in your operation. The list below is an example of some of the books and international standards that provide the necessary information and guidance.

1. Accurate Fits and Tolerance – *ISO/ANSI Shaft/Hole Tolerance Tables*
2. Clean, Contaminant-Free Lubricant – *ISO 4406*
3. Distortion-Free Equipment – *Shaft Alignment Handbook – Piotrowski*
4. Forces and Loads into Supports – *Shaft Alignment Handbook*
5. Accurate Alignment of Shafts – *Shaft Alignment Handbook*
6. High Quality Balancing of Rotating Parts – *ISO 1940*
7. Machine Vibration – *ISO 10816*
8. Correct Torques and Tensions – *ISO/ASME Bolt, Stud and Nut Standards*
9. Correct Tools in Condition – *‘As-New specification’*
10. Only In-specification Parts – *OEM specifications, Machinery Handbook*
11. Failure Cause Removal – *‘5-Why’; Creative Disassembly; RCFA*
12. Proof-test – *Precision measuring tools; Condition monitoring technologies*
13. A system to use the standards successfully – *ACE 3T, ISO9001*

This list maybe incomplete for your operation’s needs and you may have to look for additional standards to those listed above; but it is a good start. Note that there are not always international standards for every standard you need to set. In that case, use the recommendations of experts in the field. For example, when setting standards for equipment distortion and shaft alignment use the advice in John Piotrowski’s ‘Shaft Alignment Handbook’ until you need to set higher standards. At that point you maybe the world-leader in a field of expertise and you will be setting quality standards that one day we will all follow.

You will only have done the job of introducing precision maintenance well when:

- you have written and published specific precision standards company-wide

- you have held seminars to explain and discuss them with all the people that need to know and use them
- you have purchased the measuring and testing equipment you need to prove compliance
- you have written ACE 3T procedures for all activities
- you have trained people to the standards and they can achieve them competently, and
- you have a document management system that records all important equipment information over its life and allows everyone fast access to the information they need to make right decisions.

Too few companies are that good. But it does not need to be that way.

### **Engaging the Workforce**

The international benchmarking group Solomon Associates identified through their benchmarking surveys some years ago that, “Maintenance success is (ultimately) determined by decisions of craftsmen and supervisors.”<sup>84</sup> The Solomon Associates survey found that in the end what matters most in achieving maintenance and operations success is the skills and knowledge of the shopfloor people doing maintenance on the plant and equipment.

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 successful for the operation. Starting a Precision Maintenance program requires a well thought-out and structured change management process that gets your people to want to introduce and to work to higher-skilled, meticulous practices. You can do this with the ‘Change to Win’ change management team process explained in the ‘Change To Win’ workbook available on the CD accompanying this book. The ‘Change To Win’ program involves people in setting the higher standards that they have to meet, and helps them recognise the need to be up-skilled to meet them.

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<sup>84</sup> Solomon Associates, Maintenance Practice Analysis, circa 2002.

## 21. Change Management for Workplace Innovation

Change hardly ever works when forced onto people. We don't respond positively to force. You have to work with human nature, not against it. We need the opportunity to come around to it by ourselves<sup>85</sup>. That means helping people discover the good and better ways for themselves. Once they find-out how to do a thing better, and are encouraged by their managers and supervisors to use the better practices, they will be highly likely to adopt the 'change' and make it a natural part of doing their work. You want a process where people welcome 'change' and positively support it.

### 'Push the Limit' Concept

Figure 21.1 shows the 'push the limit' method of continual progress and improvement. It is the remedy used by world-class companies to protect themselves from turning into average performers. They intentionally force themselves out of their comfort zone by setting higher targets and standards to reach, and then look for the ways to reach them<sup>86</sup>. Becoming world-class means adopting the same mentality as is used by world-class organisations to get to the levels of excellence they occupy. 'Push the limit' starts the planning process.



Figure 21.1 – Push the Limit Improvement Model.

### Driving Continuous Improvement with ACE 3T Procedures

Once ACE 3T procedures are developed they become a means to push innovation and continual improvement. The advancement of work quality and skills is driven by resetting the tolerance range to one that is more demanding. Once people continuously achieve the 'good' standard, good is no longer good enough. A new 'best' practice standard is set, the 'best' standard becomes the 'better' requirements and the old 'better' is reset as 'good'. This puts the 'precision principle' into operation and harnesses people's desire to improve their skills and simplify processes. Figure 21.2 highlights how the ACE 3T standard is changed to drive improvement.

Task Step No	Task Step Owner	Task Step Name	Materials and Tools and Their Condition	Full Description of Task	Test for Correctness	Tolerance Range			Record Actual Result	Action if Out of Tolerance	Sign-off After Complete
		(Max 3 – 4 words)		(Include all tables, diagrams and pictures)	(Include diagrams and pictures)	Good	Better	Best			
Higher Standards Drive Improvement											

Figure 21.2 – Driving Quality Improvement and Innovation with Higher ACE 3T Standards.

<sup>85</sup> Carnegie, Dale, 'How to Make Friends and Influence People', Simon and Schuster, 1936.

<sup>86</sup> Wardhaugh, Jim, 'Maintenance – the best practices' Presentation, Maintenance IQ's Reliability and Maintenance Congress, 2005.

### The ‘Change To Win’ Team-Based Business Improvement Program

‘Change To Win’ is a structured change management program used to introduce needed changes, best practices and innovative improvements into an organisation. The program uses a team-based process for helping people to learn for themselves of better ways and better practices which they can include into their work. A team consisting of the manager, the supervisor and people from the affected workplace is assembled to introduce needed changes with the help of a facilitator. They are responsible to understand the issues, find the solutions and plan how the organisation will adopt the changes, including trialling the ideas and implementing them into standard practice. Together they use their individual expertise to find ways that ‘push the limit’ and bring better methods into the operation.

Internalised ideas and values can change when new knowledge is found that contradicts current beliefs and causes cognitive dissidence. The ‘Change To Win’ approach is to let people discover new knowledge for themselves and then use it to fix their problems. To give people the chance to learn new ideas and develop ownership of them, the ‘Change To Win’ program gets team members to research and investigate a range of options to address a problem. It encourages team members to go outside of their personal comfort zones and look for better practices and technology they don’t yet know of. Driving workplace evolution is the job of the ‘Change to Win’ 100-day program and its 5-Wheels of Change shown in Figure 21.3.

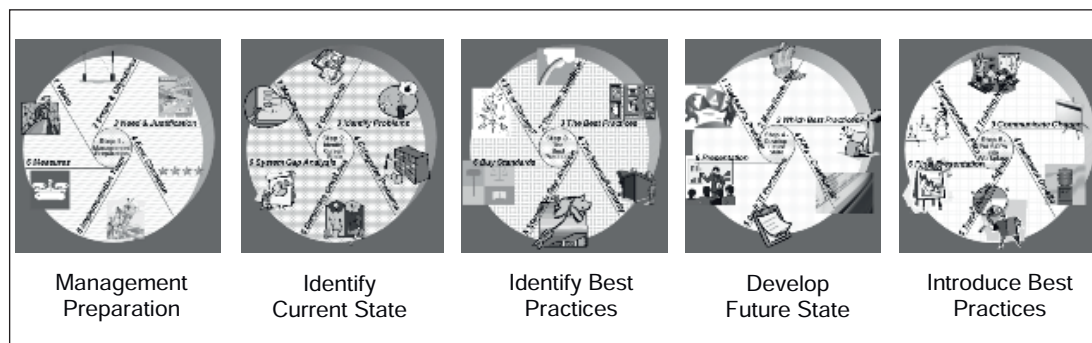


Figure 21.3 – The 5 Wheels of Change in the ‘Change to Win’ 100-Days Program.

The usefulness of an innovation to a business needs to be proven. People will only change current practices if the evidence and the support structure is in-place to make the change. A non-threatening way to do that is with a trial project to show people just how good an innovation is. A ‘Change To Win’ program is a change project limited to 100 days. 100 days is short enough for people to wait for evidence, yet long enough to do the project well. Once the ‘experimental’ project is a success, you have real proof from within the business that the change works. With each success more 100-day projects are started, until everyone becomes involved in making positive changes.

The ‘Change To Win’ approach is not for problem solving, though it can be adapted to do so. Solving problems is done with ‘Root Cause Failure Analysis’, ‘Creative Disassembly’, or the ‘5-Whys’. The ‘Change To Win’ process is a behaviour change process that improves organisational performance by introducing and integrating higher standards of performance into business processes. The ‘Change To Win’ program is used to change a company by bringing best practices into the workplace. Examples include introducing TPM (Total Productive Maintenance) into an Operation; introducing Lean Manufacturing into a manufacturer; introducing a new software system into a business; introducing an ISO 9001 quality system into a company, introducing a 5S good workplace habits program into a factory or office, and introducing Precision Maintenance into the production workforce.



## **The ‘Change To Win’ Workbook**

The ‘Change To Win’ program uses a simple workbook that each team member follows over the 100-day period. It is a friendly, low-risk, low-cost strategy to introduce changes into an operation. The teams start at the front of the workbook and each week they progress on agreed tasks until the project is complete. At weekly meetings the team reviews progress on the action plans. When the workbook is completed, the program ends.

The ‘Change To Win’ Program workbook is provided in the CD accompanying this book. It is part of the Plant and Equipment Wellness Methodology you brought. The ‘Change To Win’ workbook contains the complete change management process to apply. The workbook is self-explanatory. It uses a team facilitator to guide and encourage the 100-day change process. The facilitator helps teams to work their way through the workbook and apply the process. They keep the team on-track and on-schedule. Like everything that people do, the more often we do it the better we become. Once a facilitator uses the ‘Change To Win’ program with two or three teams it will become second nature to them.

The example used in the workbook for applying the ‘Change to Win’ method is the introduction of Precision Maintenance into an organisation. Though shopfloor people deliver Precision Maintenance, it is Maintenance and Operations Managers that need to start the change, sustain it and keep improving it. The journey to Precision Maintenance success needs a sound, safe and encouraging method to change the way people work. Starting a change initiative like Precision Maintenance requires a well thought-out and structured change management process that gets people to want to work to new, higher-skilled precision practices. Instead of risking that your improvement project becomes another failed management fad, you use this practical process to help people buy into the change; first with their heads, and then with their hearts and souls as they see the change begin to work.



## 22. The Plant and Equipment Wellness Vision

This last chapter summarises the purpose of this book with an image of its aim, which is to provide the tools for creating a business system that produces outstanding equipment reliability and life cycle profits. Plant and Equipment Wellness brings people, processes, capital and culture together in the never ending cycle of Figure 22.1. Ongoing innovation and learning lifts the organisation and its people to world-class excellence by making excellence how they do their work.

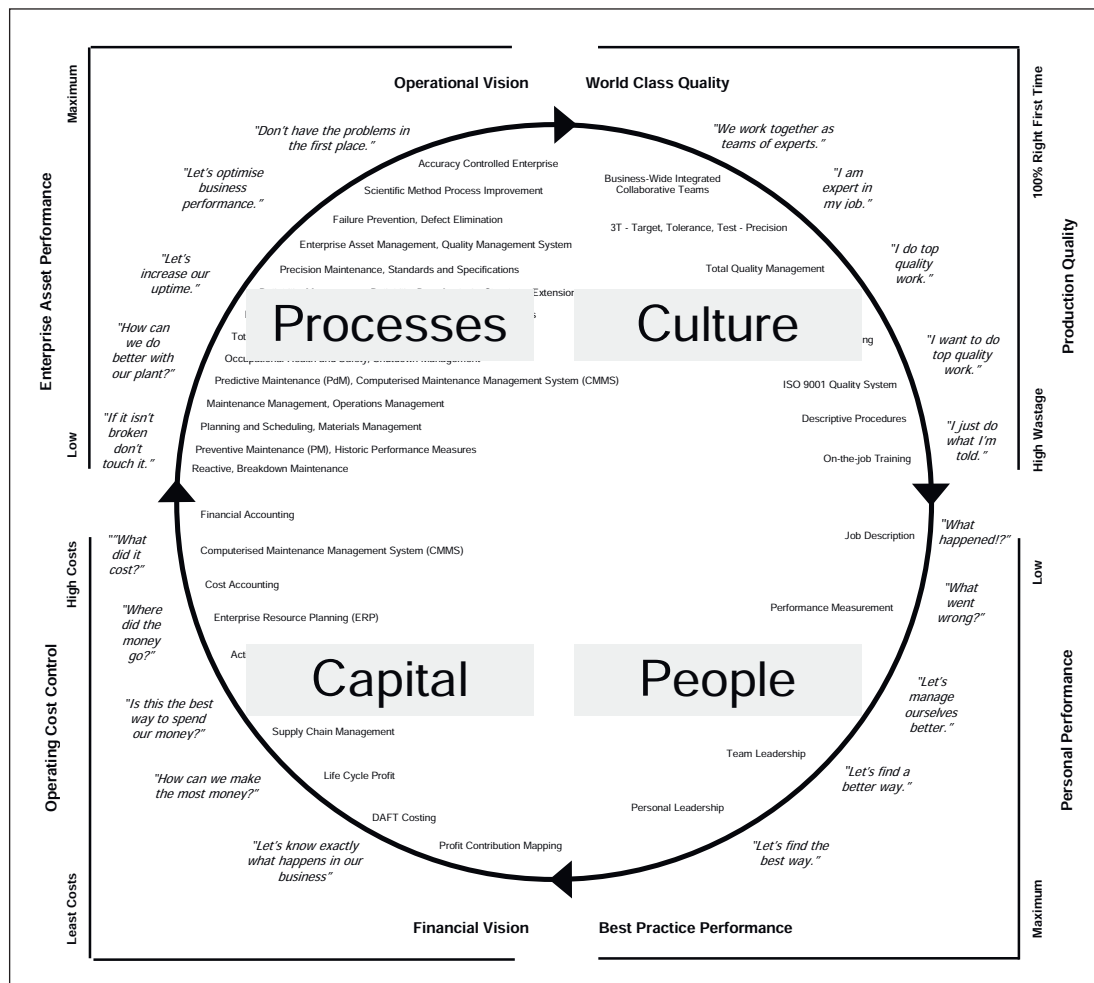


Figure 22.1 – Plant and Equipment Wellness.

What will your operation look like if you made a movie of how it performs at world class levels? Will it include adopting the necessary business processes, practices, culture and capital requirements to create an organisation that looks after the health and well-being of its machines and equipment? Focusing business-wide effort on providing for the health and wellbeing of machines and their parts may seem misguided. In a world growing ever more competitive and demanding there must be many things more important than building business systems and processes to look after machines. That of course is the trap that most industrial organisations have fallen into in the past. They don't realise that their machines support everything they want the business to achieve. No plans and dreams will be realised without machines that can make products with the quality, cost and delivery that customers willing buy. Nothing else matters to your customers but getting the best value for their money. Long-lasting success depends on

the wellness and lifetime reliability of your machines' parts. Ensuring the health of the parts automatically produces highly reliable machines, plant and equipment. An operation full of plant and equipment that never stops making top quality products, for the least cost, run by the most competent of people and working in an environment of continual learning and innovation has a great chance of success.

Start a new world-class future by mapping a path to it. What are the steps along the way? What Plant and Equipment Wellness methods and processes will you use to get world-class performance from your operation?

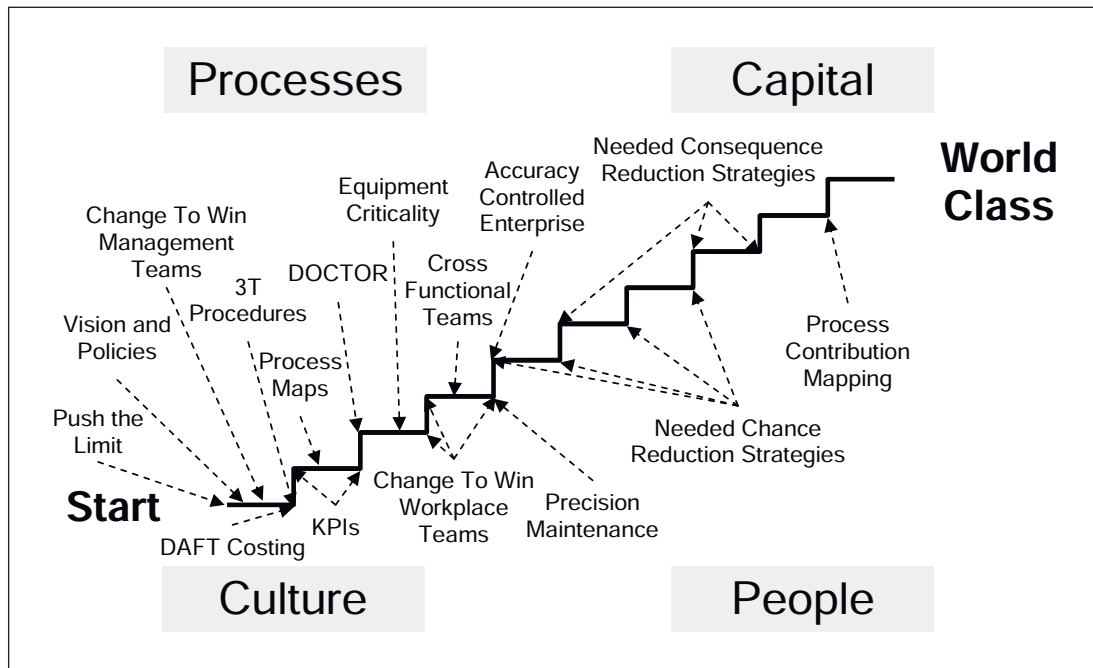


Figure 22.2 – The Steps on the Path to World Class Performance.

I hope that you now question your beliefs and understandings of what you need to do in your organisation to help it, and its people, to be the best of the best in your industry.

My best regards to you,

Mike Sondalini

[www.lifetime-reliability.com](http://www.lifetime-reliability.com)



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# Glossary

## Accounting Measures

These are summary statements containing key information covering the economic events affecting a business during a particular period, usually a month and the financial year.

Businesses use various forms of accounting for monitoring and trending. The methods usually used include financial accounting, cost accounting, managerial accounting and tax accounting. In all cases, they summarise and present business performance data that reflect the outcomes of decisions and actions taken in the past. The intention is to allow rapid detection and correction of poor performance and instigate continual improvement in future performance.

Data accuracy is critical to the proper use of accounting measures. The data needs to be timely, consistent in its gathering, of use to the user and understandable in order to make correct interpretations and decisions.

## Benchmarking

This is a method for organisations to compare their processes, practices and performance with other organisations in the industry, sometimes even across industries, to encourage striving for improvement.

Performance benchmarking is the collection of (generally numerical) performance information for making comparisons with other compatible organisations. It identifies the important performance yardsticks and permits ranking and comparing with others in the industry and other analogous industries. Ideally, repeat performance benchmarking over two or three years to monitor progress. Performance benchmarking can lead directly to improvements, but often it is an ideal pointer to improve specific processes through in-depth study using process benchmarking.

Process benchmarking is the comparison of practices, procedures and performance, with specially selected benchmarking partners, studying one business or production process at a time. It identifies what is the best practice in a process, where the best practitioners are, and what to learn from them and put to use in our own organisation.

## Common, Shared Goals

In order to produce alignment of effort and focus it is necessary to ensure diverse groups such as Operations, Maintenance and Engineering all work toward the same outcome. Giving each group the same goal insures that they work together to deliver the same result best. It minimises cross-purposes and helps focus the use of scarce resources.

An example would be that Operations, Maintenance and Engineering are each to ensure the plant and equipment has 98.5% availability in the next 12 months. Now that each group has the same target they will support each other's efforts and provide resources freely across departments. By so doing they move closer to their common goal.

### **Computerised Maintenance Management System (CMMS)**

An on-line computer accessed data base containing all useful information needed to maintain a facility's assets. It permits the planning of work, ordering of parts and spares, reporting on costs, scheduling of manpower, investigation of equipment history and other functions that improve response time and efficiency of maintenance efforts.

Integrated CMMS is one where the maintenance module seamlessly interacts with other modules in the suite to exchange data and information between the accounting, stores, human resource and manufacturing functions.

### **Detailed Scope of Work**

This is a written document describing the performance outcomes required from the person or organisation doing a task. The customer writes it to make clear to the provider exactly what outcome they want and the constraints to meet. It can include specific methods to apply in a situation, specific equipment and subcontractors to use, specific data to provide as part of the supply, specific tests to pass and standards to meet, etc.

### **Engineering Design Standards**

The purpose of Engineering Design Standards and Specifications is to provide minimum standards for the design, methods of construction, kinds and uses of materials in the preparation of plans for construction, repair or alteration of business facilities. The standards cover the current proven body of knowledge applicable to a situation or engineering issue.

Engineering and Design Standards provide information and guidelines in designing facilities. These guidelines avoid confusion during construction, operation and maintenance.

The standards may indicate compliance with specific legal requirements. Standards quoted in statutory laws and regulations become Law themselves.

Standards provide proven systems and materials to efficiently build, operate and maintain facilities while satisfying the functional needs of the business. Update standards continually as new discoveries and technologies become normal practice in an industry.

### **Environmental Impact Statement**

A detailed written statement required by Government Environmental Protection Authorities. Typically a detailed report analysing the environmental impacts of proposed plans and actions, any adverse effects that cannot be avoided and the alternative courses of action available. In the report are detailed the final decisions and actions that will be taken in the case. It can also cover short-term uses of the environment versus the maintenance and enhancement of long-term productivity, along with any irreversible and irretrievable use of environmental resources.

It should include a description of the project; a description of the environment affected; assessment of the important effects of the project on the environment; justification of the project from alternative views; and a non-technical summary of its findings.

The primary purpose of an Environmental Impact Statement is to suitably address the requirements of the statutory Environmental Act. It is to provide full and fair discussion of significant environmental impacts and inform decision-makers and the public of reasonable alternatives that would avoid or minimize adverse impacts, or enhance the quality of the human environment.



### **Equipment Criticality Analysis**

A ranking technique used to order the functions of the manufacturing/production process and the equipment supporting them. It highlights their critical value to the business. Criticality analysis is divided into two segments – Functional and Equipment Criticality analysis. The purpose of the Functional and Equipment Criticality Analysis procedure is to segregate the Function as Most Critical, Critical and Less Critical and Equipment as Extreme Critical, High Critical, Medium Critical and Low Critical.

Each function is analysed and scored with respect to its failure effect on Production, Environment and Safety and criticality scores established for each effect to calculate functional criticality score.

Then equipment is analysed with respect to its effect on Production, Environment, Quality, Safety, Service level, Redundancy and Frequency of failure. Based on the score obtained the Equipment Criticality Score is calculated.

This analysis helps in fixing Operating and Maintenance policy and strategy for the equipment based on its importance to the operation.

### **Equipment Performance Standards**

At one level, these standards establish rating criteria and procedures for measuring and certifying that product and equipment performance meet minimum requirements set by Government Agencies and Technical Committees. Typically the standards check equipment performance meets occupational health, employee welfare and environmental requirements, and to rate performance on a uniform basis so that buyers and users can make proper selections for specific applications.

A second and equally important use of equipment performance standards is to specify when the equipment is operating at design specifications. Operations and maintenance use the information to control the loading and stresses placed on plant and equipment in order to run plant within its capacity and be sure it can operate to design specifications all its life.

As new performance targets are developed the Standards are continually revised and updated. Third-party assessors monitor compliance to the minimum requirements of the standard. In statutory tests you present the results to the government agencies responsible for compliance. The standards can specify the testing methods and equipment to use to do the compliance check. For production equipment they define the lower limit of performance acceptable and let operators and managers determine what level of maintenance and monitoring are required for the plant and equipment to guarantee the minimum performance.

### **Failure Modes and Effects Analysis (FMEA)**

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.

## **Hazard Audits**

The identification, assessment and control of hazards are a key business risk management and health and safety activity. The discovery and good management of hazards will significantly reduce the number and severity of workplace injuries and catastrophic incidents.

A hazard management system includes the following features.

- Identified and assessed hazards/injury factors. This includes when there are new or changed processes, machinery or equipment.
- Significant hazards identified and prioritised for control.
- There is an action plan to manage/control hazards and injury factors (particularly significant hazards that can take the business out of production).
- Remedial action identified in injury investigations is included in action/controls.
- Hazards/injury factors and their controls are recorded in a hazard register or similar.
- Actions put into motion to address the risks and dangers.
- Staffs know when and how to report hazards and injury factors.
- Regular updating of the list of hazards and injury factors.

To manage your hazards and injury factors you need to:

1. Identify the hazard and injury factors through reporting and auditing.
2. Assess the impact on the business and prioritise hazards and injury factors for resolution.
3. Control hazards and injury factors by developing and implementing actions to control them.
4. Regularly evaluate the effectiveness of the control actions.

All these steps need completion to create an effective hazard management system that will prevent injuries and business catastrophes from happening.

As with all health and safety activity, the hazard management process will be far more effective when employees are involved, and trained managers lead the process.

## **Hazard Identification Study (HAZID)**

This is the first step in risk assessment and hazard management. The results input directly into planning and setting safety objectives. HAZID is a similar process to HAZOP, involving pre-work, a documented team exercise using tailored check-lists and prompt lists, and the subsequent tracking of actions through to close out. The process of hazard identification is relevant throughout the life-cycle of a project.

Several techniques of HAZID exist, including conceptual hazard analysis and layout assessment. All of which systematically evaluate a plant, process or system to determine the hazards present. These techniques ensure objectivity by including independent personnel on the review team and assist in the demonstration of hazard management by the use of formal records. Ranking of identified risks ensures efforts focus on areas of higher risk.

## **Hazard and Operability Review (HAZOP)**

These are six systematic and integrated studies conducted to identify safety, health and environmental aspects and operability problems of processes through all stages of the project life cycle.

**HAZOP 1 (Preliminary Hazard Review)**

Perform it at the very early stage of any project or modification. It identifies the safety, health & environmental aspects of the materials in the process that need further attention. Also, provide information for compiling the Environmental Impact Assessment.

**HAZOP 2 (Plant and Equipment Major Hazard Review)**

Carried out at the conceptual design stage on the feasibility phase plant and equipment to identify and assess hazards in terms of fire, explosion, and toxic release. This provides information for Major Hazard Installation Risk Assessments.

**HAZOP 3 (Detailed Examination of the Design)**

It identifies hazard and operability problems at the completion of the basic design, which could originate from deviations in the design.

**HAZOP 4 (Plant Review)**

After construction and before commissioning, this review ensures that all the provisions from the previous studies are incorporated in the built plant.

**HAZOP 5 (Safety Health and Environmental Audit)**

This review checks legal and organisational risk management programs for compliance before start-up.

**HAZOP 6 (Operational Review)**

This final review confirms that the operation meets all the Safety Health and Environmental requirements and is operable.

**Installation Check Sheets (Also see Rotating Equipment Integrity)**

Charts, tables, records that list the plant and equipment precision maintenance standards for construction and the actual site field measurements attained.

The acceptable tolerance ranges on the check sheets are from information provided by the OEM, and from the previously set precision maintenance standards specified for the equipment.

**KAIZEN Continuous Improvement**

It is a Japanese concept that encourages small continuous improvement daily. It focuses on doing things better without spending much money; involves everyone from managers to workers and uses simple common sense solutions. It is ongoing, never-ending progress where established practices are gradually improved.

Kaizen methods work in a number of ways. The most common is to change worker operations to make a job more productive, less tiring, more efficient and safer. To get buy-in, and gain significant improvement, invite workers to participate in the process. With the help of a supportive team, ask how to more efficiently and simply do the job. Gradually introduce the changes. A second way is to improve the equipment, like providing foolproof devices (poka-yoke) or changing the machine layout to speed up a process. A third outcome is to redesign the procedures.

Conduct a review first to identify areas and functions of potential benefits, or problem areas needing improvement. There are opportunities for improvement in every business function.

The Kaizen process needs to be controlled. Do not change designs, layouts or standards unless there is definite improvement. The control is normally through using improvement groups where rank or position is unimportant and where improvement suggestions from all are encouraged. An authoritative committee further discusses the suggestions to insure they have worth and gain to the business. It is normal to reward appropriately those suggestions that are valuable to the organisation.

The best success with Kaizen comes when it is applied to make improvements in the workplace ('gemba' is the word for workplace in Japanese). The workplace is where the actions taken, the procedures used and the decisions made will affect the profitability of the business. By asking people in the workplace to find better ways to do their work they gradually introduce changes and improvements that simplify and speed-up the outcomes they produce.

### **Key Performance Indicator (KPI)**

This is where you evaluate and optimise the performance of the business using metrics. One of the greatest challenges faced by a company's executives is optimising the results of its business performance. Businesses can use metrics to generate and analyse key performance indicators (KPIs) to measure the success of its efforts and continuously improve so they can meet and exceed future expectations.

When you know what goals you should set for your business, specify and define a KPI to track their achievement, and performance. This helps the people involved in its achievement to succeed faster.

### **Leadership toward World Best Practices**

Leadership is the ability of the leader to think, reason, calculate, inform and act so that a group of people produce performance and results beyond the sum of each individual's abilities. In particular the focus is on continually looking for better ways to deliver outcomes and drive the business toward world leading performance, through its people growing and developing in competence and self-esteem.

### **Lean Waste Reduction**

Lean waste reduction is the concept of eliminating waste in production conversion and in process flows. The lean production philosophy emphasises maximising the effectiveness of production processes. At the same time the ratio of actual outputs to the inputs should also be maximised.

This approach involves the basic idea that activities other than pure conversion are non-value-adding tasks, thus generating waste. A working principle is to continually reduce the cost of non-value-adding activities. It becomes important to minimise flows that generate waste. In the lean thinking approach, management and optimisation of processes focus not only on the improvement of conversion activities but also concentrate the efforts at reducing inefficient flows. It provides a way to manage unnecessary work and uncertainties. These escape notice during common operating and production practice. To improve the operating systems you have to address both optimising conversion activities, and cut waste by reducing unnecessary flows.

Major principles of lean waste reduction for flow design and production improvement are:

- a) The reduction of variability during production.

- b) The continuous improvement of the processes to eliminate waste in all its forms.
- c) Control over the whole process (conversion and flows).

The reduction of variability is one of the most important challenges in lean thinking. One way to reduce variability is to bring each process under control so you know what will happen. Another way to eliminate variation is by anticipating the variation root causes and addressing them in the equipment design, and in the future operating and maintenance practices.

### **Life-Cycle Cost Analysis (LCCA)**

This is a method for assessing the total cost of facility ownership. It takes into account all costs of acquiring, owning, and disposing of a building or building system. LCCA is especially useful with project alternatives that fulfil the same performance requirements, but differ with respect to initial costs and operating costs. Select the one that maximises net life-time savings. LCCA will help determine the cost-effective alternatives that dramatically reduce operating and maintenance costs during the life of a project, even though they may increase initial capital cost. LCCA is not useful for annual budget allocation.

The LCCA estimates the overall costs of project alternatives to select the design that ensures the lowest overall cost of ownership consistent with necessary quality and function. Do the LCCA early in the design process while there is still a chance to refine the design to ensure a reduction in life-cycle costs.

### **Maintainability**

Defined by the military as “The relative ease and economy of time and resources with which an item can be retained in, or restored to do its function. With maintenance performed by persons having specified skill levels, using set procedures and resources, at each prescribed level of maintenance and repair. In this context, it is a function of design.”

You design Maintainability into a plant. Designing for maintainability requires reducing the time equipment will be down and unavailable. It goes beyond reducing the time saved by having a highly trained workforce and a responsive supply system to achieve minimum downtimes. Designing for maintainability requires an item of plant to be serviceable (easily repaired) and supportable (cost-effectively kept in or restored to a usable condition).

Attempts to improve the inherent maintainability of an item after the design is finalised are usually expensive, inefficient and ineffective. With plant and equipment built and installed, its maintainability is set, and to improve it requires major changes later during operation. If the simplest maintenance efforts need a crane to extract an item from inaccessible areas of the plant, or a major shutdown of equipment to insure safety, it is clear that both maintenance costs and production downtime are greatly increased. If maintainability were part of the plant design, such equipment maintenance would be quick and simple to maintain.

Achieving excellent maintainability requires the use of sound planning, engineering, plant and equipment design, testing, excellent quality conformance, adequate supply and support systems for spare parts, competent and trained people, additional skills development, and the ability to incorporate lessons learned from past problems or previous similar equipment.

It is well worth spending a great amount of time in simplifying the maintenance requirements of plant and equipment, as over one third of all future maintenance costs and time losses are attributable to maintainability factors.

### **Maintenance Standards and Procedures**

This collection of documents specifies the minimum level of performance functions and conditions for operating the facility and its equipment to deliver design output. It includes:

- defining what level of in service performance plant and equipment will operate at (typically an availability measure or a OEE target);
- the level of presentation and cleanliness needed in the facility, and its plant and equipment.

Setting standards and making them public knowledge will make the requirements of managing the facility, along with the proper operation of the equipment clear to everyone and easy to encourage and achieve.

### **Management Reporting**

To insure the operation is running efficiently and troubling issues are being addressed it is important that people know how the business is performing, what the relevant issues are for the business and how they are being resolved. This necessitates using a method to capture and pass relevant information to the people that need it. Such a system is a management reporting system.

Typically, it allows the integration of operating processes with business systems to provide real-time business information across the operation. It reduces duplication of administrative activities; streamlines planning and budgeting processes; and uses both financial and non-financial performance measures to track performance throughout the operation.

The timeliness of information will make the management reporting system either a useful tool with which to manage the business, or a millstone that prevents rapid response to changed conditions and innovative opportunities. Its processes need to deliver timely, accurate, relevant, consistent, accessible management information useful to making the business successful.

A good management reporting system will allow:

- The frequency of information to be optimal to decision making.
- Whenever possible the original data is real-time input by users and be in a consistent format.
- Central systems to be sufficiently flexible to capture any data considered relevant by users.
- Users get direct access to data, and the tools to derive and analyse management information.
- The data and its conversion processes into useful information to facilitate and improve management decisions.
- Information is available to all units and managers to measure performance against quantifiable performance goals.
- Decision-making is on the substance of the decision rather than the quality or consistency of the data.
- Full financial impacts of decisions on cost and revenues to be analysed before making decisions.

### **Net Present Value (NPV)**

An approach used in capital budgeting where the present value of cash inflow subtracts from the present value of cash outflows. If the resultant flow is positive then the investment should make money.



NPV compares the value of a dollar today versus the value of that same dollar in the future, after taking inflation and return into account. You should accept a prospective project if the NPV is positive. However, if it is negative, reject it because the money flows are negative.

The net present value method of evaluating a major project allows you to consider the time value of money. Essentially, it helps you find the present value in “today’s dollars” of the future net cash flows of a project. Then you can compare that amount with the amount of money needed to do the project. If the NPV is greater than the cost, the project will be profitable (assuming, of course, that assumptions made to estimate the cash flow are reasonably close to reality). If you have more than one project on the table, you can compute the NPV of both, and choose the one with the greatest difference between NPV and the cost to do.

### **Overall Equipment Effectiveness (OEE)**

*Thanks to Don Fitchett from [www.bin95.com](http://www.bin95.com).*

A metric used to save companies from making inappropriate purchases, and continue poor practices, so helping them focus on improving the performance of machinery and plant equipment they already own. It is a measure of the “effective” utilisation of equipment within its scheduled runtime.

Typically Operational personnel often have little control over the scheduled runtime of equipment (these often being determined by such factors as overall market demand, and senior management capital allocation decisions), and so OEE is an effective measure reflecting what factors they can control.

The overall performance of a single piece of equipment, or even an entire factory, results from the cumulative impact of the three factors that comprise the OEE figure – availability, quality and performance:

Availability is the measure of the percent of time that the equipment can be used (usually total hours of 24-7-365), divided by the equipment uptime (actual production) percent of scheduled production (reliability) or calendar 24-7-365 time (equipment utilisation), that the equipment is available for production.

Performance efficiency is the percentage of available time that the equipment is producing product at its theoretical speed for individual products. It measures speed losses (e.g., inefficient batching, machine jams). It is the percent of parts produced per time frame of maximum rate specified by the original equipment manufacturers (OEM) rated production speed. If the OEM’s specification is not available, use best-known production rate over a four-hour period.

Quality Rate is the percent of the total output (i.e. all production produced including rework and scrap/waste) that is good. It is the percent of good sellable parts out of total parts produced per time frame.

The OEE = (Availability % x Performance % x Quality rate %) and the result indicates how productive the plant has been during the period of time the measurements were made.

### **PM Optimisation**

A shorter version of RCM used on existing plants with sufficient history of known failure modes. Instead of starting at the beginning and brainstorming possible failure modes, PM Optimisation starts with the known failure modes for the equipment in the plant. In plant and equipment operating for many years, the actual failure modes are in site-specific historical data. It greatly shortens the entire failure evaluation process and lets you set into place the right PM inspections for your plant.



## **Planning and Scheduling**

Planning is a necessary function within any organisation that produces something. In the manufacturing and processing environments, this function is often complex because of the rate of change, range of production, and occurrences of unplanned events. There are several different methodologies to choose from depending on the demand for the product and the rate of change. Nevertheless, the objectives of efficiency (minimisation of waste) and effectiveness (supply to demand) remain the same for each.

Planning is used to co-ordinate activities and limited resources to achieve goals right-first-time. Planning must be done so that the progress of the plan can be monitored at regular intervals and control over separate operations can be maintained. Planning involves five elements: definition, labour planning, scheduling, equipment planning and cost planning.

- Definition means specifying the scope and extent of the work performed.
- Scheduling involves specifying the start, duration, and end of the various activities,
- Labour planning involves allocation of personnel, distribution of responsibilities and resources,
- Equipment planning involves identification of types and need of equipment,
- Cost planning involves identifying costs and their occurrence.

## **Precision Maintenance Standards**

This involves the installing, operating and maintaining of equipment to the running tolerances required by current best practices. Adopting a precision maintenance philosophy and setting high standards extends machinery life spans between failures (reliability) enormously and so increases profits.

To achieve this it is necessary to set-up equipment aligned to close tolerances, balanced so vibration is within acceptable low limits and operated stress-free and deformation-free so it can function exactly as designed.

## **Precision Operating Standards**

These are similar to standard operating procedures (SOP) but with specified operating condition tolerances for plant and equipment. It involves defining the range of process variation considered to be acceptable for the plant and equipment to meet its planned operating life while delivering quality and throughput requirements.

The purpose is to remove stressful occurrences on equipment and materials of construction and extend the length of failure-free plant operation. The measures monitor the equipment loads and stresses on the materials of construction so to ensure original design specifications throughout the equipment's operating life. It uses visual management to display timely process performance data to the operations people so they can adjust conditions to keep equipment within design envelopes.

## **Predictive Maintenance (PdM)**

This proactive approach to maintenance detects the onset of equipment degradation. This allows elimination or control prior to any significant deterioration in the physical state of the component or equipment. The benefits include improving both the current and future functional capabilities of the equipment and increasing its reliability.

Predictive maintenance differs from preventive maintenance by basing maintenance needs on the actual condition of the equipment, rather than on some predetermined schedule. Typically, preventive maintenance is time-based or throughput based. Activities such as changing lubricant are time dependent, like calendar time or equipment run time. For example, most people change the oil in their vehicles every 10,000 to 15,000 kilometres travelled. This is basing the oil change needs on equipment run time. There is no concern of the actual condition and performance capability of the oil. The schedule dictates the change, not because it needs to be changed.

This approach is equivalent to a preventive maintenance task. On the other hand, if the driver of the vehicle instead had the oil analysed to determine its actual condition and lubrication properties. Then he or she may be able to extend the oil change until the vehicle had travelled another 5,000 kilometres. This then is the fundamental difference between predictive maintenance and preventive maintenance. Predictive maintenance defines needed maintenance tasks based on inspection and measurement to quantify material and equipment condition against an acceptable standard. Until the standard is breached the equipment remains in service.

**Advantages:**

- Provides increased component operational life and availability since remaining life is monitored,
- Allows for pre-emptive corrective actions before failure,
- Results in decrease in equipment and/or process downtime, as rectification work can be planned,
- Lowers costs for parts and labour since only true problems are actioned,
- Provides better product quality as deterioration is monitored,
- Improves worker and environmental safety by proactive measurement,
- Raises worker morale because they see the true equipment condition,
- Increases energy savings,
- Results in an estimated 8% to 12% cost savings over a preventative maintenance program.

**Disadvantages:**

- Increases investment in diagnostic equipment so real-time measures are trended,
- Increases investment in staff training to build competency of analysis,
- Management may not readily see the savings potential without first doing a trial to prove its worth.

There are many advantages of using a predictive maintenance program. A well-orchestrated predictive maintenance program will all but eliminate catastrophic equipment failures. Use schedule maintenance activities to minimize or eliminate overtime costs. Inventory is minimised, as orders for parts go out when needed to support anticipated maintenance. Equipment will be operated at an optimal level, which will also save energy costs and increase plant reliability.

Depending on a facility's reliance on a reactive maintenance approach and material condition, savings opportunities of 30% to 40% are possible. In fact, independent surveys indicate

the following industrial average savings resulted from initiation of a functional predictive maintenance program:

- Return on investment: 10 times
- Reduction in maintenance costs: 25% to 30%
- Elimination of breakdowns: 70% to 75%
- Reduction in downtime: 35% to 45%
- Increase in production: 20% to 25%

The down side of using a predictive maintenance approach is its initial costs. The up-front costs of starting this type of program can be expensive. Much of the equipment requires substantial expenditure, though low entry cost products are now available. Alternately, subcontract the program and service to a proficient provider who provides reports and advice. Training of in-plant personnel is necessary to effectively utilize predictive maintenance technologies and practices. That will require additional funding.

Beginning a predictive maintenance program requires an understanding of the opportunities available to the facility and the approaches to take to get those benefits. It is also essential to have a firm commitment by the organisation's management and staff to make it work. The safest approach is to appoint an able person to conduct trials in an area of plant with a bad maintenance history and monitor the improvements achieved.

### **Preventative (Preventive) Maintenance (PM)**

Wear, tear, and ageing are normal in this maintenance program. It applies continuous corrective actions to ensure peak efficiency and correct deterioration in equipment.

PM involves a planned and controlled program of systematic inspection, adjustment, lubrication, and replacement of components along with in-service operational performance testing and analysis. The result of a successful PM program extends the life of the plant and equipment, and minimises unscheduled downtime that causes major problems. It ensures that equipment parts operate properly, and breakdowns minimised.

A PM system is time based or scheduled on unit of production. It reviews the condition of existing equipment listed in a CMMS database. PM work orders generate from the CMMS at designated frequencies for each piece of equipment.

There needs to be a proactive review and analysis of equipment to identify the most cost-effective service tasks and time cycles. Optimise the service tasks and time intervals for equipment in the PM system, as the understanding of maintenance requirements for a piece of plant improves.

As new equipment comes on line, a maintenance mechanic can gather nameplate data in the field. The data is reviewed with reference to the manufacturer's manuals, and assigned initial service tasks and intervals before the data input personnel enters it to the PM system. As the PM system runs, a service/failure history will develop for each piece of equipment, and data extracted by equipment type.

Equipment grows old, uses change, and techniques vary. Important elements to monitor closely include an assessment of appropriate PM tasks, as well as proper frequency. An effective preventive maintenance program is not static, but needs regular review and updating in order to remain viable and effective.

## **Project Management Indicators**

A project comprises a set of measurable objectives aimed to achieve a desired outcome. The objectives are definitive, time specific and measurable by some metric. Accomplishing an objective can involve many people, require specific resources and involve an extensive series of process tasks.

The primary objectives of project management include time, resource, quality and risk management.

- Time management is concerned with accomplishing the project within a given timeframe.
- Resource management addresses labour, materials and equipment needed to accomplish the project.
- Quality management focuses on meeting the requirements for the project.
- Risk management is being aware of and responding to potential delays or impediments to accomplishing the project.

A project is a planned set of milestones to achieve within a set time and cost.

- A project plan communicates what work to do to those involved.
- Those involved with plan can anticipate their contribution to the project.
- Management has a means to monitor and measure progress and costs.
- Anticipate and manage unexpected events that may impact the project.

The primary objectives of project management are planning, scheduling monitoring and controlling.

- Planning determines what needs doing, who does it, and how to achieve the objective
- Scheduling when the work will occur.
- Monitoring involves tracking task accomplishment in relation to time, cost and resource use.
- Controlling is concerned with responding to unanticipated occurrences or circumstances.

The planning and scheduling functions are the key elements of the project management process. Together they involve six steps.

- Identify activities that must be performed to complete the project
- Estimate the time required to complete each task activities.
- Develop a project plan to sequence the task activities.
- Schedule task activities assigning a start and finish date to each one.
- Review the schedule to determine if it is reasonable and complete.
- Implement the schedule.

Applying project management techniques enhances the prospects for success by providing methods to control, co-ordinate and measure key factors affecting completion.

## **Quality Function Deployment (QFD)**

Product users judge a product by the ways it is actually used, rather than the ways its designer imagined it used. Therefore, the procedure for developing new products and new production facilities starts with finding out what the (potential) customers want and how that can be technically achieved. QFD takes the quality characteristics specified by the customer and

turns them into 'engineer-able' features. The purpose of QFD is to find out what the customers want or need, how much they will pay for it, what the competition is doing, and then translate that knowledge by logical stages into a competitive design, complete with manufacturing instructions. QFD is concerned with economic quality of design and ensuring satisfactory product service, without excessive maintenance needs or restrictions on its operation. The value of QFD lies in organising and correlating the marketing information into a form that is useful for production. It translates customer wishes, first into engineering features and then into detailed product designs that meet those wishes.

It is a formal technique that attempts to get "the voice of the customer" echoed into the design and manufacture of the product. The customer says, for instance, "What we really are worried about is the comfort of the ride." The marketing group does some comparisons against competitive models. Then they go to the engineers, and the engineers say, "What does a comfortable ride translate into? It's related to the thickness of the seat, and to the suspension system." They break down the desired characteristic, a "comfortable ride," into its subsidiary engineering design aspects. Once they get it fine-tuned enough -- it requires, say, a change in the amount of lubrication in the shock absorber -- they reflect those changes in the way they manufacture shock absorbers.

### **Quantitative Risk Assessment (QRA)**

A Quantitative Risk Assessment is a credible scenario of analysing the risk for a specific project. The methodology is to identify, quantify and evaluate the risks to operations involving hazardous materials. The purpose of the assessment is to reduce risks to a level that are 'as low as reasonably practicable' (ALARP), which are acceptable to the community hosting the operation.

Third party persons assess the likelihood of danger. They calculate the consequences and severity should the danger arise. Preferably, design-out and eliminate the problem. If that is not possible methods of local containment within a set area are used. In addition, put management and control methods to continually monitor the danger and address any occurrence into place.

### **Records Management**

The systematic gathering of key information into a catalogued database where it is accessible to help make better decisions in the future based on facts from the past. There is a need for good record management in an organisation. The control of records may be due to statutory/legal requirements to prove compliance, future purchasing of exact duplicate items for current operating plant and equipment and the future review of key decisions taken in the past to check their remaining validity for the organisation.

Records management is the application of systematic controls concerning the creation, maintenance and destruction of records required in conjunction with the operation of an organisation. File the records using a logical and defined scheme into a managed repository, available for retrieval by authorised principals. The records management system is foremost about storage and maintenance, and has responsibility for maintaining the integrity of the records, facilitating back-up, and assisting users in filing and retrieval.

The chief duties of a records management system are filing, searching, retrieval, creating retention schedules, transfer, destruction, etc. all are part of managing the life cycle of a record.

A record is a unit of recorded information, generated or received by an organisation, which acts as evidence of activities. Most records are in the form of a document, although records

in other forms are possible. The notion of a record encompasses the roles the underlying document plays within an organisation over time. Including the relationship the participant in an organisation has to that record, and the relationship between the record and other records.

When the information in the record has declined in value, remove it from active accessibility. Depending on the nature of the record, destroy it immediately, or keep in archives for a set period. Preserve records that have a sustaining utility exceeding storage costs permanently in an archive.

### **Redundancy and Duplication**

This controls risk in key production systems by intentionally duplicating equipment that has poor mean time between failures, or where the consequence of failure is too catastrophic.

### **Regulations, Laws and Standards**

The requirements put into place by government decree to continue operation of the project, operation or business.

The regulations, laws and standards require all persons to read them and to understand their obligations. Where necessary ask the regulatory bodies responsible for policing the upholding of the requirements to provide additional information and guidance in interpreting the requirements.

### **Reliability Centred Maintenance (RCM)**

RCM is a structured and formulaic process used to decide what to do to ensure that any physical asset, system or process continues to operate as its users want.

Users define what they expect from their assets in terms of primary performance parameters such as output, throughput, speed, range and carrying capacity. Where relevant, the RCM process also defines what users want in terms of risk (safety and environmental integrity), quality (precision, accuracy, consistency and stability), control, comfort, containment, economy, customer service and so on.

The next step in the RCM process is to identify ways in which the system can fail to live up to these expectations (failed states), followed by an FMEA (failure modes and effects analysis), to identify all the events which are reasonably likely to cause each failed state.

Finally, the RCM process seeks to identify a suitable failure management policy for dealing with each failure mode in the light of its consequences and technical characteristics. Failure management policy include: – predictive maintenance – preventive maintenance – failure-finding – change the design or configuration of the system – change the way to operate the system – run-to-failure.

The RCM process provides powerful rules for deciding whether any failure management policy is technically appropriate. It also provides precise criteria for deciding which and how often to do routine tasks.

### **Risk Based Inspection (RBI)**

Risk based inspection considers the probability of failure and its consequences. The technique aims to bring better value for money from inspection.



It is now widely accepted that the traditional time-based approach to planned plant inspection by a competent person has a number of shortcomings. In particular, the use of fixed intervals between inspections may be too conservative and lacks the freedom to benefit from good operating experience. The introduction of goal setting legislation has facilitated a move towards risk based strategies, which focus inspection resources on parts of the plant that carry greater risks where preventing failure will have the greatest benefit.

RBI is a technique to underpin and direct planned plant inspection. It claims to offer the prospect of cost savings resulting from the better targeting of resources. RBI recognises that there is little point to spending good money, for example, on very frequent inspection of something that is very unlikely to fail, or if it did fail would have little financial or safety consequence. In line with the principles of ALARP (as low as reasonably practicable) the money saved may be better spent elsewhere. Savings can also arise from reduced direct inspection costs.

### **Root Cause Analysis (RCA)**

The method brings a team of 3 to 6 knowledgeable people together to investigate a failure using evidence left behind from the fault. The team brainstorms to find as many causes of the fault as possible. They construct a fault tree starting with the final failure and progressively tracing each cause that led to the previous cause. By using what evidence remains after the fault and from discussions with people involved in the incident, dismiss all non-contributing causes from consideration and retain the contributing causes.

This continues until the trail can be traced back no further. Each result of a cause must clearly flow from its predecessor (the one before it). If it is plain that a step is missing between causes, add it in and look for evidence to support its presence.

Once the fault tree is completed and checked for logical flow the team then determines the changes to make to prevent the sequence of causes and consequences from again occurring.

It is not necessary to prevent the first, or root cause, from happening. It is merely necessary to break the chain of events at any point and the final failure cannot occur. Often the fault tree leads to an initial design problem. In such a case, redesign is necessary. Where the fault tree leads back to a failure of procedures, address the procedural weakness or to install a method to protect against the damage caused by the procedural failure.

The cause tree explains step-by-step how the events leading to the incident unfolded. It is necessary to prevent one failure cause and there would be no failure.

### **Rotating Equipment Integrity**

This method aims to ensure process equipment safety and reliability. Because of the many factors that can affect the reliability of rotating equipment. Guidance notes and checklists for inspections are developed. They contain sufficient detail to make informed and rational judgements during inspection visits, on the state and general health of safety critical areas of machinery and rotating equipment. It covers the development of inspection notes on major safety issues for process machinery and rotating equipment used on offshore and onshore installations. It focuses on the equipment included within commonly applied machinery and rotating packages. It contains a review process used to assess a complete installation, in order to help an inspector understand the impact of operating culture, and context on the safe operation of machinery and rotating equipment installations.



## Six Sigma Quality

‘Six Sigma’ focuses on preventing problems by building quality into processes – by not having problems in the first place. The Six Sigma methods utilizes full-time dedicated project managers (Green and Black Belts) who receive formal classroom training in process analysis and statistical methods as well as mentoring by Six Sigma experts. The Black Belts then work within the company as “problem-solvers for hire.” They lead process improvement projects, and focus on areas that will have the highest impact on the bottom line.

Six Sigma stands for 3.4 defects per one million opportunities.

- 3 Sigma – 66,800 defects per one million opportunities.
- 4 Sigma – 6,210 defects per one million opportunities.
- 5 Sigma – 233 defects per one million opportunities.
- 6 Sigma – 3.4 defects per one million opportunities.

The Six Sigma methods start by asking the fundamental question: What is critical to the customers? All processes in the business get rigorous analysis to assess whether they are delivering what customers require. Each time processes don’t deliver what the customer wants it is a defect.

Six Sigma is rooted in fundamental statistical and business theory; consequently, the concepts and philosophy are very mature. Applications of Six Sigma methods in manufacturing are common and the process well understood. It follows on the heels of many quality improvement programs.

Six Sigma is passionate about using data to uncover the root causes of those defects and eliminating them from the processes. It used data to understand the process variability and drive process improvement decisions. The ultimate objective is to deliver to customers what is critical to them each and every time – to produce “virtual perfection” from the customer’s perspective.

A Six Sigma improvement team is responsible for identifying relevant metrics based on engineering principles and models. With data/information in hand, the team then proceeds to evaluate the data/information for trends, patterns, causal relationships and “root cause,” etc. If needed, conduct special experiments and modelling to test hypothesised relationships or to understand the extent of leverage of factors. You can accomplish most improvement projects with the basic statistical and non-statistical tools. On achieving the target level of performance, put control measures in place to sustain it.

Common sense and force of personality are not means to reach dramatic improvements. The only way is to ask the tough questions and to use rigorous statistical and financial analysis. When problems reduce, costs decline and customer satisfaction improves. Six Sigma delivers business results that can accelerate growth, reduce costs and ultimately deliver excellent profits.

## Supply Chain Management (Logistics)

It is about getting a smooth and efficient flow from raw material to finished goods in your customer’s hands. It is a concept that is increasingly replacing traditional fragmented management approaches to buying, storing and moving goods.

Traditionally, the management of material flows centred on stocks of product: on the movement of trains, and boats and trucks, and in the contents of warehouses and stores and factory-floor queues. Managing those stocks meant buying enough goods far enough in advance to ensure that long, steady production runs were seldom jeopardised by shortages of

components. Tougher competition has brought shorter product life-cycles and made the old stocking approach increasingly expensive. Now replacing these ‘inventory-driven systems’ are the ‘service-driven systems’. This type of system, which is ‘pulled’ by customer demand rather than ‘pushed’ by a supply system, has become a necessity in many manufacturing sectors.

In the past, companies have dealt with moving and storing goods in unrelated ways, and under a number of different managers. In manufacturing, transport from supplier to plant was handled by suppliers themselves or by a purchasing department. The stores department handled transport and storage of stores within the plant, and manufacturing or maintenance operations handled movements within the plant. Transport from plant to customer was handled by transport or distribution departments; buying was handled by purchasing; sales forecasts by marketing and communicated to manufacturing and procurement in a generally one-way information flow.

This approach splits functional departments into watertight compartments when, as every manager knows, business is not like that. Particularly in this area, where the essence of supply chain management is managing flows across departments, sites and – often – companies. This approach takes a high degree of management integration.

Logistics deals with geography, time and value. Many of its concerns are with things in places and transport between the places. In this view, logistics deals with everything from raw materials, through their movement into and between various stores, and the processes to the customer. It looks at material flows within sites as much as between sites.

### **Shewhart Control Charts**

Control charts were developed in the 1920s by W. A. Shewhart as a means to monitor variation in production processes. Shewhart observed production supervisors reacting to common cause production problems and instead of reducing variation they made production performance worst. To help identify when a problem was caused by the process itself or by an external factor, he devised control charts based on three sigma limits that assumed normal distribution of events. The presumption was that a process would of itself produce random variation. Provided the variation was within the behaviour of random chance, then it was caused by the process and thus was uncontrollable without changing the process. If an event was beyond the three sigma upper or lower limit, it was an outlier that very likely had a special cause which had to be addressed to ensure it would not again impact process performance.

The obvious problem with control charts is that a special cause problem ‘hides’ within the three sigma limits and appears to be a process issue because it does not produce outlier effects. The way to find such problems is to first solve the identifiable special cause problems you can and stabilise the process so it runs for a long time within its three sigma limits. Then you improve the process performance so the spread of process results tightens closer to the required target. This will expose more special causes to address until the process is again producing only its own random variation. You then repeat process improvement in the same way until it becomes uneconomic to do more.

### **Total Effective Equipment Productivity (TEEP)**

It is a percentage figure that represents the portion of good quality production versus total time during the period being measured. Typically used as a measure of the “effective” utilisation of equipment assuming continuous 24 hour/day, 365 day/year operation. Useful to senior management who should be concerned more with total return on assets employed, and is a more effective performance measure at this level.

## **Total Productive Manufacturing (TPM)**

This is a methodology that can slash unit costs in manufacturing and process industries by ensuring that plant and equipment are used to their maximum effectiveness. It can bring significant competitive advantage. TPM promotes best of breed practices and is used to secure:

- Business performance improvement.
- Cultural change and people benefits.
- Competitive advantage in the market place.

Company-wide TPM recognises that it is customers who drive the business. It aims to provide the necessary responses to not only satisfy, but also to exceed the expectations of customers. The goal is to maximise added value by eliminating waste in all that is done, right across the supply/value chain.

TPM is a Continuous Improvement process that strives to maximise equipment efficiency by creating the perfect relationship between people, their processes and equipment. It has five founding principles:

- Increase the Overall Equipment Effectiveness (OEE) through focused improvement.
- Make front-line Asset Care part of the job.
- Improve existing planned maintenance systems and the quality of maintenance.
- Increase hand/operational skills and team working and problem solving skills.
- Early Equipment Management: Involve operators and maintainers in the next generation of equipment design (TPM for Design).

TPM is both practical and results driven. Applied to the shop floor, it is a common sense approach that provides visibility to all the six major losses that are a result of poor equipment performance. The resultant Business Performance Measure is called the Overall Equipment Effectiveness (OEE).

The TPM process must be led by manufacturing and encourages production and maintenance departments to work in harmony as a team, with the goal of increasing equipment effectiveness and in turn the organisation's profitability.

It also involves other departments, such as supply chain administration, sales and marketing, warehousing and distribution, as well as the more direct manufacturing support functions of design, quality, production control, finance and purchasing which are concerned with equipment and process effectiveness. This of course includes management and supervision. TPM makes extensive use of waste elimination, standardisation, workplace organisation, visual management and problem solving.

Like all good business improvement tools TPM must be tailored to suit the specific organisation and plant.

## **Total Quality Management (TQM)**

*Thanks to Ron Kurtus of Kurtus Technologies for this information.*

The basic principles for the Total Quality Management (TQM) philosophy of doing business are to satisfy the customer, satisfy the supplier, and continuously improve the business processes.

The first and major TQM principle is to satisfy the customer--the person who pays for the product or service. Customers want to get their money's worth from a product or service they

purchase. If the user of the product is different than the purchaser, then both the user and customer must be satisfied, although the person who pays gets priority.

A Company that seeks to satisfy the customer by providing them value for what they buy and the quality they expect will get more repeat business, referral business, and reduced complaints and service expenses. Some top companies not only provide quality products, but they also give extra service to make their customers feel important and valued.

Within a company, a worker provides a product or service to his or her supervisors. If the person has any influence on the wages the worker receives, that person can be thought of as an internal customer. A worker should have the mind-set of satisfying internal customers in order to keep his or her job and to get a raise or promotion. Often in a company, there is a chain of customers, – each improving a product and passing it along until it is finally sold to the external customer. Each worker must not only seek to satisfy the immediate internal customer, but he or she must look up the chain to try to satisfy the ultimate customer.

A second TQM principle is to satisfy the supplier, which is the person or organisation from which you are purchasing goods or services.

A Company must look to satisfy their external suppliers by providing them with clear instructions and requirements, and then paying them fairly and on time. It is only in the company's best interest that its suppliers provide it with quality goods or services, if the company hopes to provide quality goods or services to its own external customers.

A supervisor must try to keep his or her workers happy and productive by providing good task instructions, the tools they need to do their job and good working conditions. The supervisor must also reward the workers with praise and good pay. The reason to do this is to get more productivity out of the workers, as well as to keep the good workers. An effective supervisor with a good team of workers will certainly satisfy his or her internal customers.

One area of satisfying the internal supplier is by empowering the workers. This means to allow them to make decisions on things that they can control. This not only takes the burden off the supervisor, but it also motivates these internal suppliers to do better work.

The third principle of TQM is continuous improvement. You can never be satisfied with the method used, because there always can be improvements. Certainly, the competition is improving, so it is very necessary to strive to keep ahead of the game. Some companies have tried to improve by making employees work harder. This may be counter-productive, especially if the process itself is flawed. For example, trying to increase worker output on a defective machine may result in more parts that are defective.

Examining the source of problems and delays and then improving them is necessary. Often the process has bottlenecks that are the real cause of the problem. You must remove these. Workers are often a source of continuous improvements. They can provide suggestions on how to improve a process and eliminate waste or unnecessary work.

There are also many quality methods, such as just-in-time production, variability reduction and poka-yoke (mistake proofing), that can improve processes and reduce waste.

The principles of Total Quality Management are to seek to satisfy the external customer with quality goods and services, as well as your company internal customers; to satisfy your external and internal suppliers; and to improve processes continuously by working smarter and using special quality methods.

# Index

## Symbols

3Ts of defect elimination, 167-170  
3W2H, 260-261  
5-Whys, 260, 261-262, 270  
14 Points of Management, 213, 219

## A

accuracy control, 36, 164, 171  
Accuracy Controlled Enterprise, v-xiii,  
37, 102, 131, 148, 152, 163-180, 172, 266-269  
accuracy controlled procedures, 70  
ACE 3T, 82, 126, 132, 144-147, 172-174,  
180, 247-248, 256, 266-269  
Activity Based Costing, 54, 193  
asset management and wellness policy, 78  
asset management policy, 78  
autonomous work team, 158

## B

Bathtub Curve, 242  
benchmarking, 216, 268, 275

## C

capital justification, 231  
carpenter's creed, 10-11, 163  
chance reduction, 113, 122, 133-139, 141, 143  
change reduction, 131  
Change To Win, 104, 186, 239, 254, 268, 270-271  
Chart of Accounts, 54  
CMMS, 65, 82, 102, 108, 143-147, 226, 231, 238, 244,  
256, 276, 286  
cognitive dissidence, 270  
common cause, 29, 33, 89, 220, 238, 257-259  
Computerised Maintenance Management System, 65, 82,  
102, 108, 226, 276  
condition monitoring, 22-23, 50, 81, 130-132, 142-144,  
147, 238, 240-241  
consequence reduction, 113, 122, 130, 133-139, 143  
consequence reduction techniques, 133  
continual improvement, ix, xii, 269, 275  
control chart, 40-41, 91  
cost map, 55, 192-193, 198-200  
cost of failure, 45-47, 53-54, 60, 113, 117, 120, 139  
cost surge, 2, 133  
creative disassembly, 255-257  
critical success factors, 193  
criticality analysis, 115, 128, 147, 295  
cross-functional team, 130, 142, 147, 160-162  
cross-hair game, 25, 29, 33, 41, 162  
Crow-AMSAA, 82, 86, 243, 249-250, 295

## D

DAFT Cost, 2, 49-50, 54-56, 65, 70-72, 81, 109, 112-122,  
128, 139, 143, 146, 231, 238, 241, 259, 261  
Defect and Failure Total Costs, 2, 54

defect elimination, 43, 96, 122, 132, 138, 142, 168, 170-172  
degradation cycle, 22  
degradation management, 243  
Deming Cycle, 90  
Deming, W. Edwards, 27, 30, 37, 87, 213-214, 219-220  
Design and Operations Cost Totally Optimised Risk, 68  
Design-out, 130-131  
DOCTOR, 68, 70-72, 100-101, 122  
downtime cost, 228  
DuPont, 41, 76, 295

## E

Enterprise Asset Management, viii-x, 75-78, 97, 102, 116,  
127, 244  
equipment criticality, 114-117, 120, 132, 141, 143, 147  
Equipment Criticality, 74, 80, 100, 114-116, 139, 141, 143,  
241, 277  
equipment failure, 2, 7, 17, 26, 30, 44, 50, 65, 70-71, 77, 93,  
100-101, 113-114, 131, 139, 143, 229, 241, 256-257  
equipment reliability, vii-xii, 5, 15-16, 30, 38-39, 42,  
61-62, 80, 83, 87, 97-98, 122-125, 136, 140, 144, 154-  
158, 164-168, 170-171, 187, 214, 221-222, 229-230,  
238, 241, 245, 248, 266-267, 272  
error-proof, 26, 168  
error-proofing, 10, 14

## F

failure mode, 128-131, 148, 230, 243-248, 277, 289  
Failure Mode, 65, 80, 100, 115-116, 127-129, 142, 238,  
296  
Failure Mode and Effects Analysis, 80, 100, 115, 128-129,  
142, 238  
Failure Mode Effects and Criticality Analysis, 127  
failure patterns, 240  
failure prevention, 43, 53, 96, 132, 138-139, 168  
failure pyramid, 139, 256  
failure scenarios, 43  
fault tree, 258-259, 290  
Fault Tree, 257-259, 260  
Fault Tree Analysis, 257  
Finite Element Analysis, 19  
fixed costs, 44-46, 199-200  
FMEA, 65, 100, 127-132, 142-144, 147, 238, 241  
FMECA, 100, 122, 127-130, 147, 152, 244, 277, 289, 295  
frequency of an event, 107, 115, 130

## H

HAZOP, 101-103, 278-279  
hidden factory, 35  
hierarchical organisation, 162  
human error, ix, 5, 14-15, 23, 65, 86, 126, 245  
human factor, ix, 26, 87

## I

Instantaneous Costs of Failure, 49

ISO 4406, 32, 39, 267, 296  
ISO 9001, 75, 163, 270, 296

## J

Japan Airlines, 12-13  
job quality, 167-169

## K

Key Performance Indicators, 186, 208-210, 218-220, 254

## L

Latent issues, 261  
Lean, x, 64, 89, 104, 160, 163, 172, 270, 280, 295  
life cycle, vii, 14, 19, 42, 61-62, 65, 68, 70-72, 76-77, 97,  
101, 132, 135, 241, 245-247, 263, 266, 272, 278, 288  
life cycle profits, 61, 68, 272  
lubricant contamination, 30

## M

machine vibration, 29, 263-264  
maintenance management, x-xii, 8, 19, 76, 220, 238, 255  
maintenance policy, 79- 80  
maintenance procedures, 23, 131  
maintenance standards, 101-103, 266, 279  
maintenance strategy, ix, 65, 79, 141, 148, 242  
maintenance work order, 221-222, 230  
materials of construction, 4, 17-20, 106, 245, 284  
Mean Time Between Failure, 234, 250  
Mean Time To Repair, 230  
Monte Carlo simulation, 244

## N

Nolan and Heap, 240-241

## O

organisation structure, 157  
out-of-calibration, 265  
Overall Equipment Effectiveness, 106, 212-213, 283, 293

## P

parallel process, 10, 156  
parallel tasks, 13, 124  
Pareto chart, 227, 259  
PAS 55, 75, 296  
Physics of Failure, 16-19, 34, 132, 144  
Plant and Equipment Wellness, ix-xiii, 61-65, 75-78, 114-  
115, 119, 127-129, 141, 173, 187, 241, 271-273  
plant availability, 38, 42, 80-82, 106, 128, 154, 238, 263  
power laws, 136-137, 249  
precision maintenance, 103, 126, 132, 148, 164, 238, 249-  
250, 256, 263-268, 279, 284  
Precision Maintenance, 80, 103, 131, 249, 255, 263-271,  
284  
precision principle, 269  
preventive maintenance, 21, 32-33, 100, 120, 131-132, 142,  
230, 238, 240, 286, 289  
probability, 5, 8, 16-18, 31-39, 74, 91, 109-112, 123-128,  
139, 157, 230, 240-243, 289  
probability of failure, 8, 33-39, 123-124, 230, 289  
Process Boundary Method, 211-212  
process chains, 3  
process maps, 2, 63-65, 75, 100, 124, 130, 143-146, 245  
Process Step Contribution, 187, 192-93

Process Step Contribution Mapping, 55, 172, 186-195  
process variability, 291, 33-36, 41-43  
proof-test, 11, 170  
proof-testing, 12, 126  
push the limit, 214, 269-270

## Q

quality control system, 160  
Quality Function Deployment, 99, 287  
quality management system, 75, 163, 172, 265

## R

random failures, 231, 238, 243  
reactive culture, 135  
Reliability Centred Maintenance, 22, 127, 240-241, 289,  
296  
reliability engineering, 16-19, 76  
reliability growth, x, 8, 245-249, 255  
Reliability Growth Cause Analysis, 115-116, 127, 142,  
147, 245-247, 254  
Return On Investment, 8, 213  
risk analysis, 34, 64-65, 70-74, 82, 108, 113-115, 132, 140,  
241  
risk boundary, 74, 112-113  
risk control plan, 130  
Risk Control Plan, 122, 130  
risk equation, 45, 60, 107-109, 112-113, 133-137  
risk management, xii, 65-68, 76-82, 101-120, 128-141,  
169, 241-243, 278-279, 287  
risk matrix, 74, 107-117, 128, 141-148  
risk ranking table, 110  
risk reduction, 72, 100, 107-108, 116, 127, 135-138, 143-  
148, 241  
Root Cause Failure Analysis, 241, 255-257, 270  
run chart, 27, 36

## S

Series Reliability Property, 8, 93, 248, 255, 260  
series system reliability, 8  
shaft misalignment, 39, 124  
silo hierarchy, 160  
softfoot, 256  
special cause, 29, 33, 89-93, 148, 220, 257  
Standardisation, 89  
standard operating procedures, 87, 166-168, 194, 284  
Standard Operating Procedures, 13, 165-169  
strength-of-material, 17  
stress concentration, 20

## T

target, tolerance, test, 168  
Terotechnology, 75  
Time Series, 227, 233, 238, 248  
timeline, 228-230, 248  
Titanic Disaster, 133, 139  
tolerance bands, 169, 180  
Total Productive Maintenance, 147, 186, 270

## U

Upper Control Limit, 36

## V

value stream mapping, 64, 187, 189

Value Stream Mapping, 172  
variability, 24-29, 33-43, 77, 89, 105, 168-171, 280-281,  
291, 294  
variable costs, 44-49, 199-200  
voice of the customer, 99, 288  
volatility, 24, 33-37, 89-91, 193

## **W**

Weibull Analysis, 242-244, 250  
Weibull parameters, 242, 244  
Why Tree, 260  
work quality assurance, 162, 172



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Mike has authored numerous maintenance and industrial asset management publications and developed the [www.feedforward.com.au](http://www.feedforward.com.au) UPTIME training series for chemical and process plants. His current programs for business – “The Accuracy Controlled Enterprise” and “Change to Win Program” – inculcate ultra-high reliability best practices into organisations within 100 days. Mike is a past Chairman of the WA Chapter of the Maintenance Engineering Society of Australia and is a confident and exciting presenter at Australian and international conferences and workshops. His professional qualifications include BEng(Hons), MBA, CPEng.

