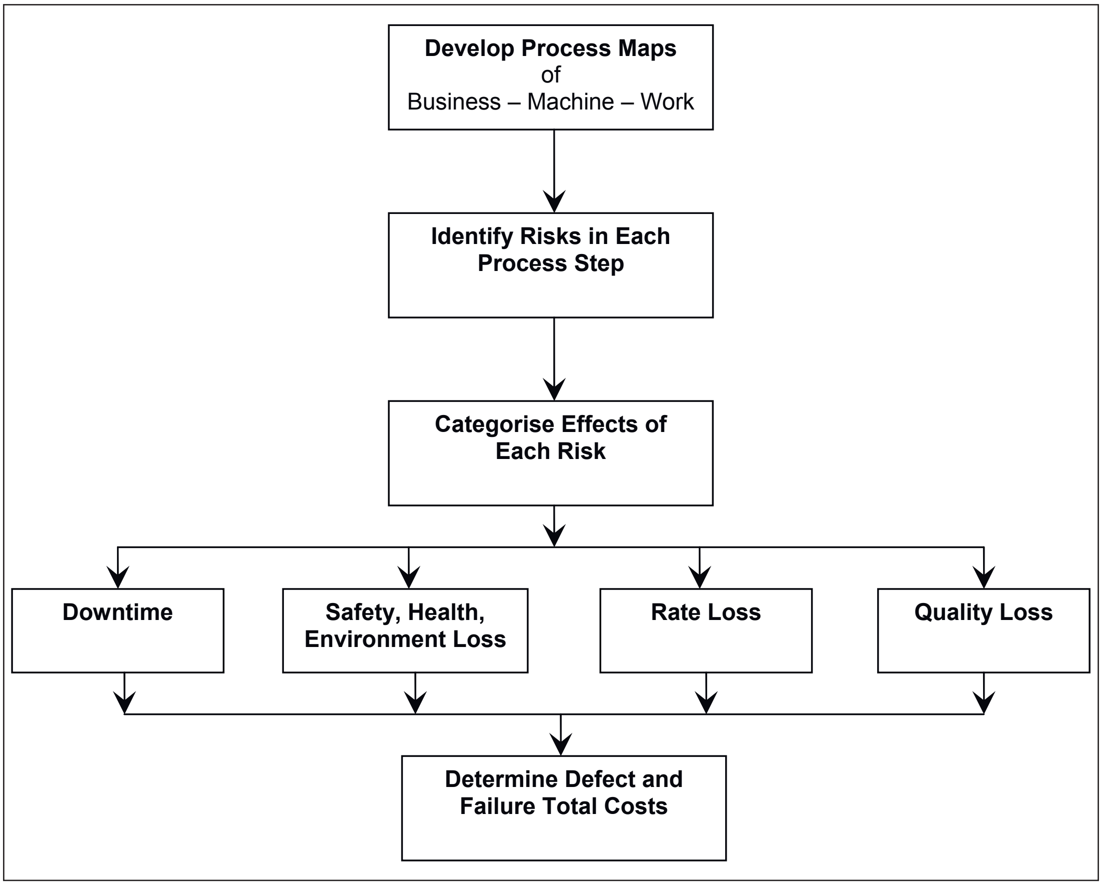
PROCESS 1 – Operating Risk Identification



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 [2].

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.

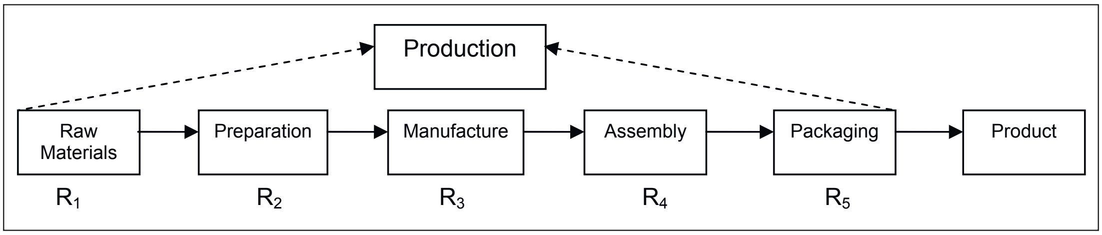


Figure 1.1 – A Series of Steps in a Production Process.

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

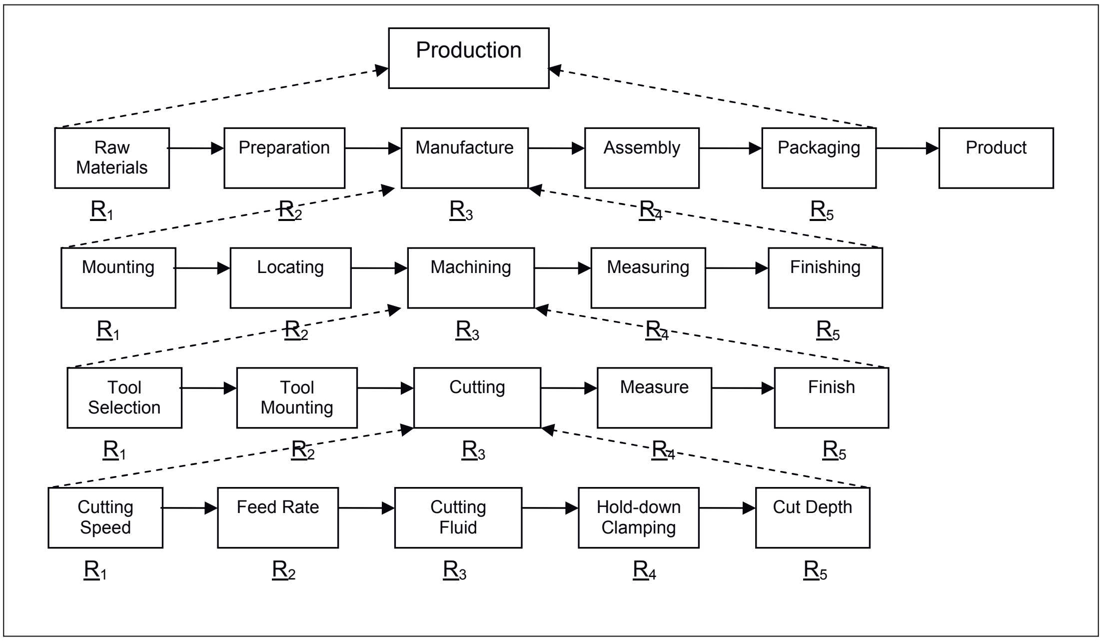


Figure 1.2 – There are Numerous Work Sub-Processes in Every Production Process.

[2] 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.

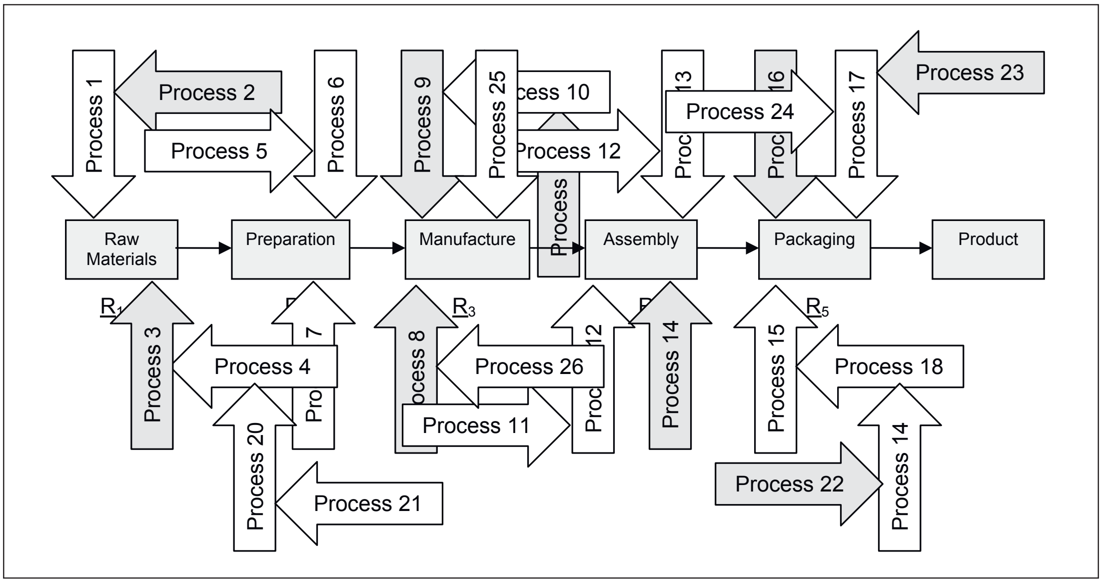


Figure 1.3 – Numerous Processes Interact across Every Process Chain.

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 [3].

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

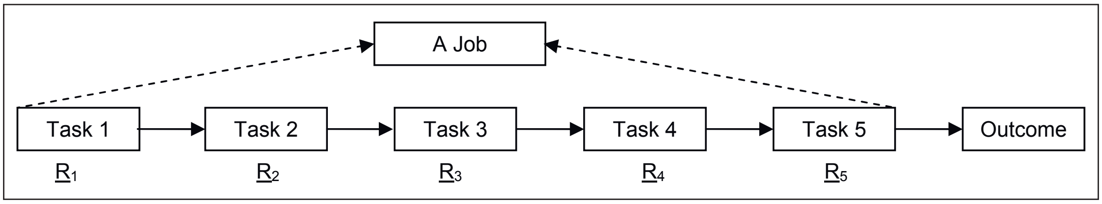


Figure 1.4 – A Series of Tasks in a Work Process.

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 '$\underline{R}$' acts to differentiate the modelling of work process reliability from component or system reliability (which does not use the underscore).

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

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[4]. 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:

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

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%.

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

[4] 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
	Routine simple tasks		
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
	Routine task with care needed		
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
	Complicated, non-routine task		
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.

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

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

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.

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

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

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 arrangments. 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 [5]. 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.

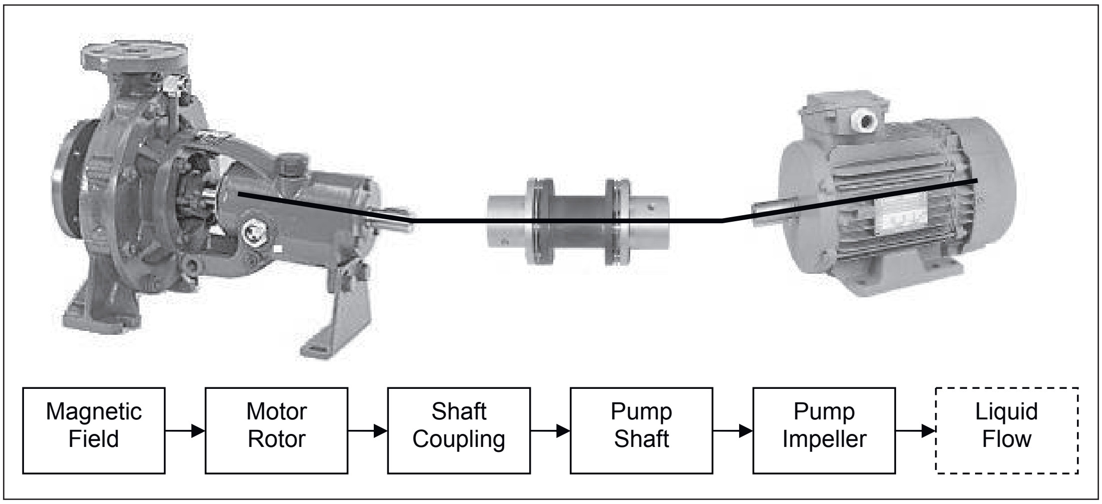


Figure 1.5 – Series Arrangement of Parts in a Centrifugal Pump-set.

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

$$R_{series} = R_1 \times R_2 \times R_3 \times \ldots R_n \qquad \textit{Eq. 1.2}$$

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.

[5] 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 x 0.8 = 0.72, which is less than the reliability of the least reliable item. Even if work was done to lift the 0.8 reliability up to 0.9, the best the system reliability can then be is 0.9 x 0.9 = 0.81.

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

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

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

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

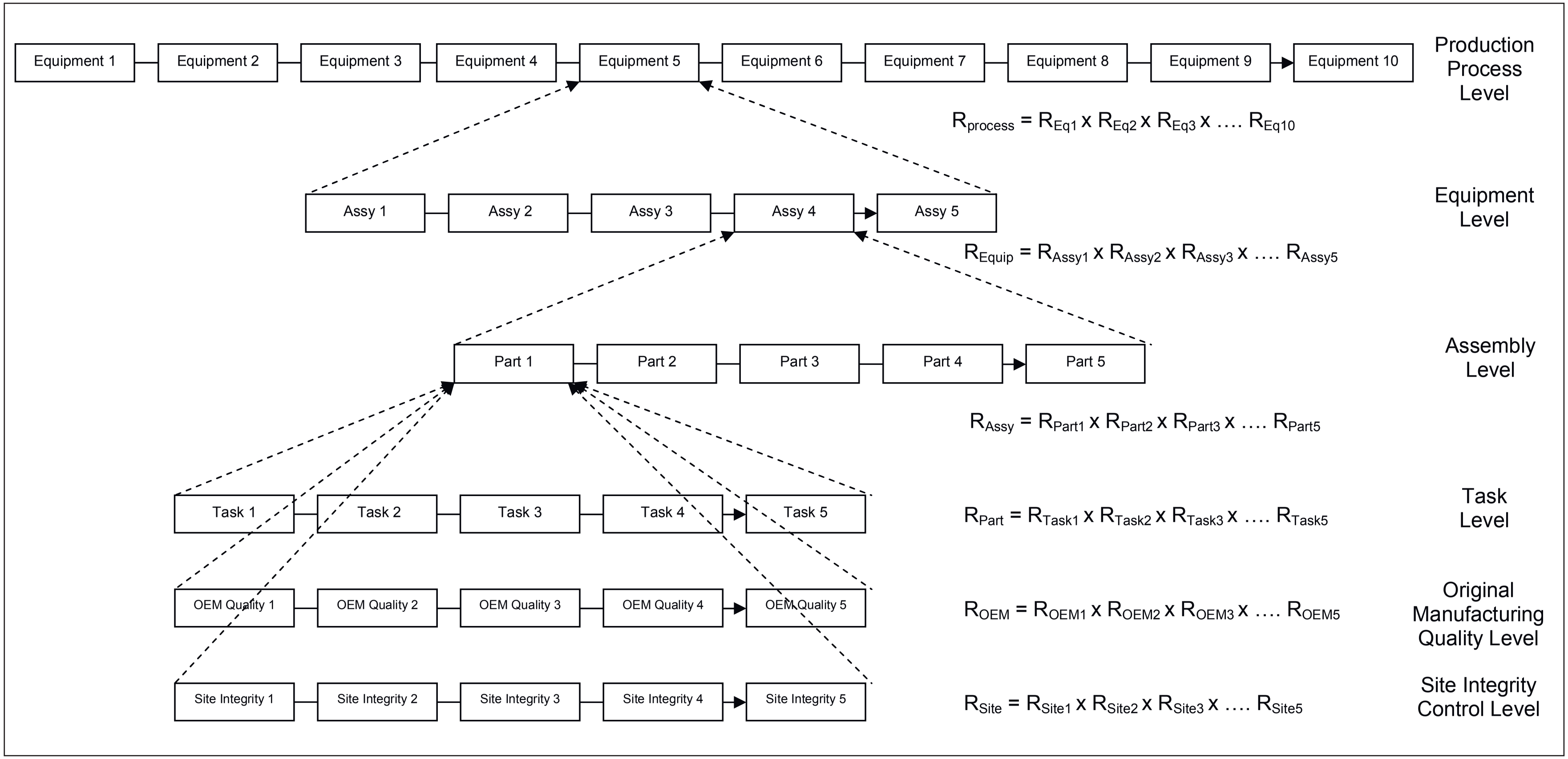


Figure 1.6 – Reliability Applies to Every Aspect of an Operation and Its Equipment throughout the Life Cycle.

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.

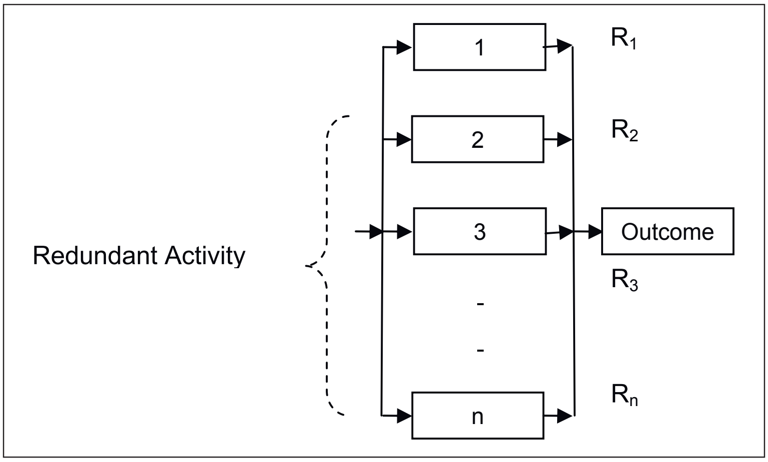


Figure 1.7 – A Parallel Process.

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).

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

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

$$\underline{R} = 1 - [(1\text{-}0.6) \times (1\text{-}0.6) \times (1\text{-}0.6) \times (1\text{-}0.6)]$$
$$= 1 - [(0.4) \times (0.4) \times (0.4) \times (0.4)] = 1 - [0.0256]$$
$$= 0.9744$$

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.

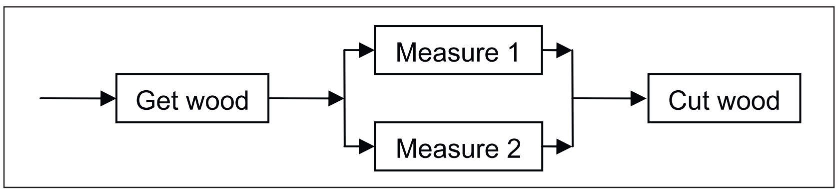


Figure 1.8 – 'Measure Twice and Cut Once', the Carpenter's Creed, is a Parallel Activity.

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'.

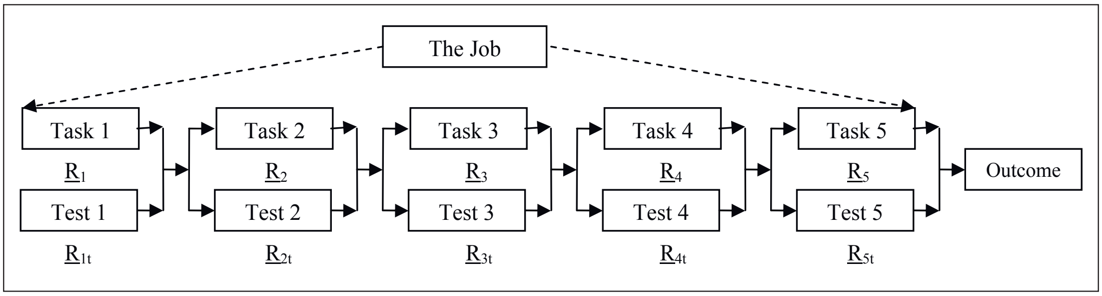


Figure 1.9 – A Parallel Tasked Work Process.

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:

$$\begin{aligned} \underline{R}_{task} &= 1 - [(1 - \underline{R}_1) \text{ x } (1 - \underline{R}_{1t})] \\ &= 1 - [(1\text{-}0.9) \text{ x } (1\text{-}0.99)] = 1 - [(0.1) \text{ x } (0.01)] = 1 - [0.001] \\ &= 0.999 \ (99.9\%) \end{aligned}$$

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:

$$\underline{R}_{job} = 0.999 \text{ x } 0.999 \text{ x } 0.999 \text{ x } 0.999 \text{ x } 0.999 = 0.995 \text{ (i.e. } 99.5\%)$$

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.

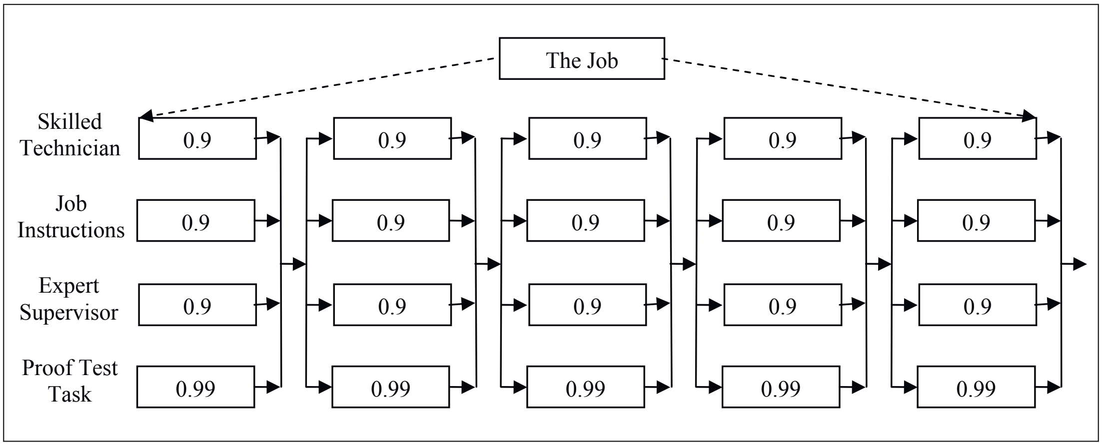


Figure 1.10 – A Multi-Paralleled Task Work Process.

The reliability equation for these paralleled work tasks is:

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

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

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

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.

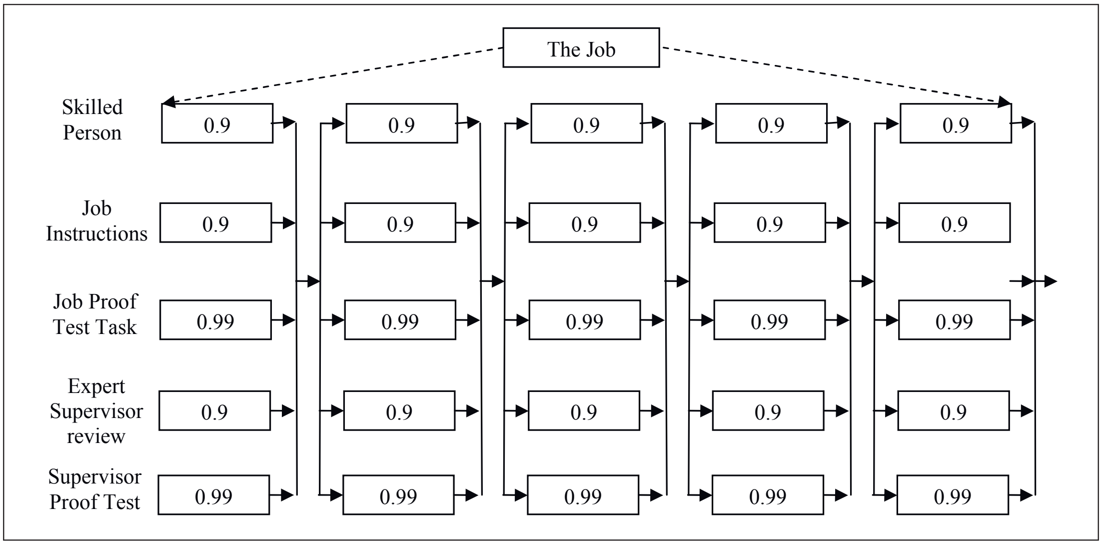


Figure 1.11 – Super-Sure Error Prevention Work Process.

The reliability of each paralleled error preventing step is now:

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

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

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

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 [6]. 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:

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

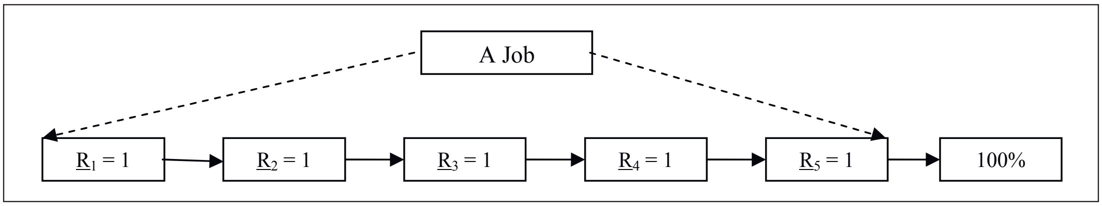


Figure 1.12 – A Series Tasked Work Process with each Task Totally Error-Proofed.

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 [7]. 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.

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6 Gladwell, Malcolm, 'Blink, the power of thinking without thinking', Back Bay Books, 2005.

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

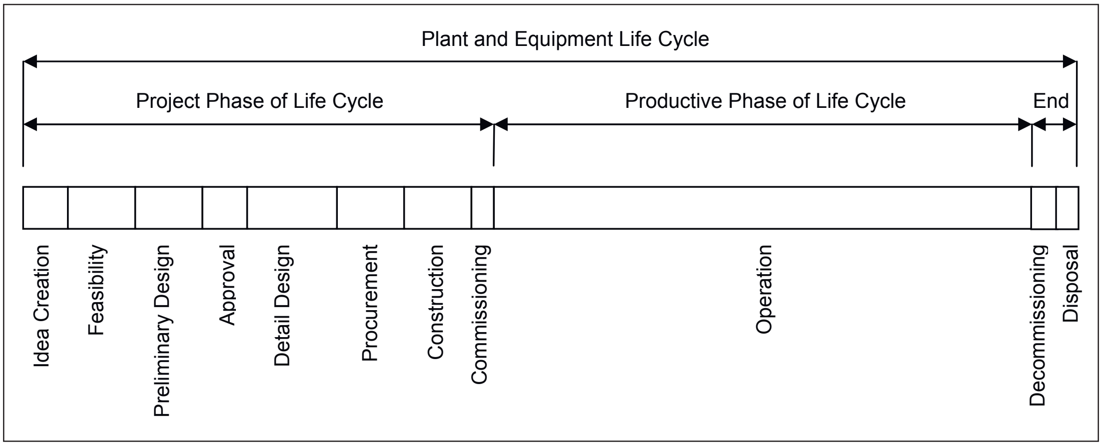

Figure 1.13 – The Life Cycle of an Industrial Facility involves Multitudes of Series Process.

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.

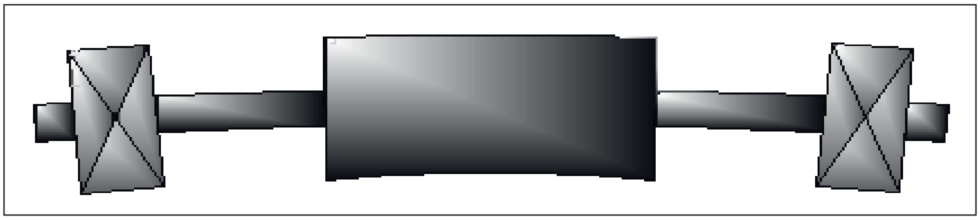

Figure 2.1 – Machine Distortion Overloads Parts.

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.

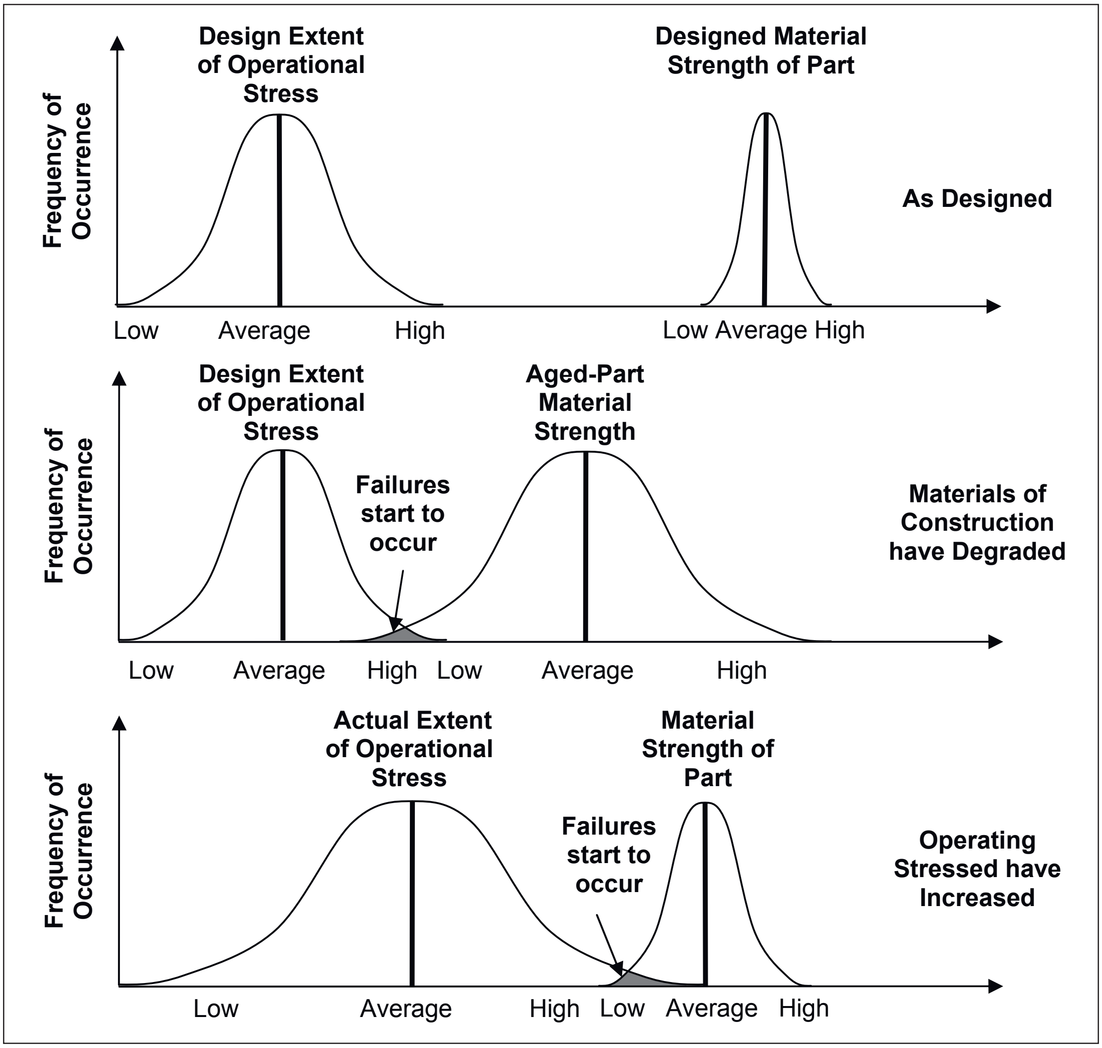

Figure 2.2 – Parts Fail When the Stress in Parts is Greater than the Strength of Parts.

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.

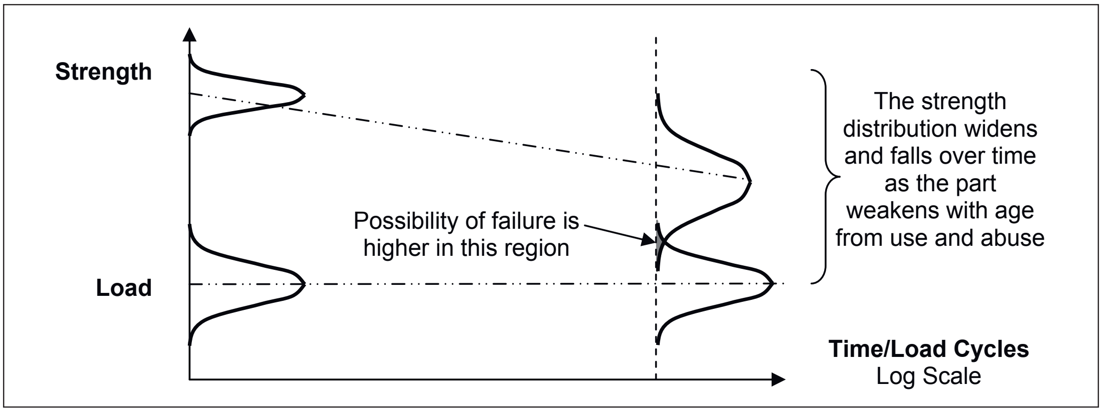

Figure 2.3 – Time Dependent Load and Strength Variation as Stress Damage Accumulates.

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.

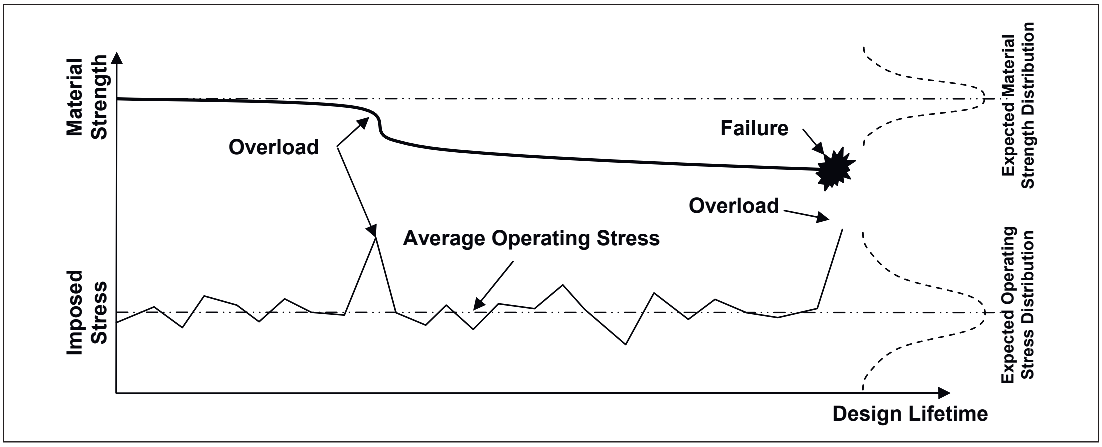

Figure 2.4 – Effects of Overload Stresses on the Failure of Parts.

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 [8]. 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.

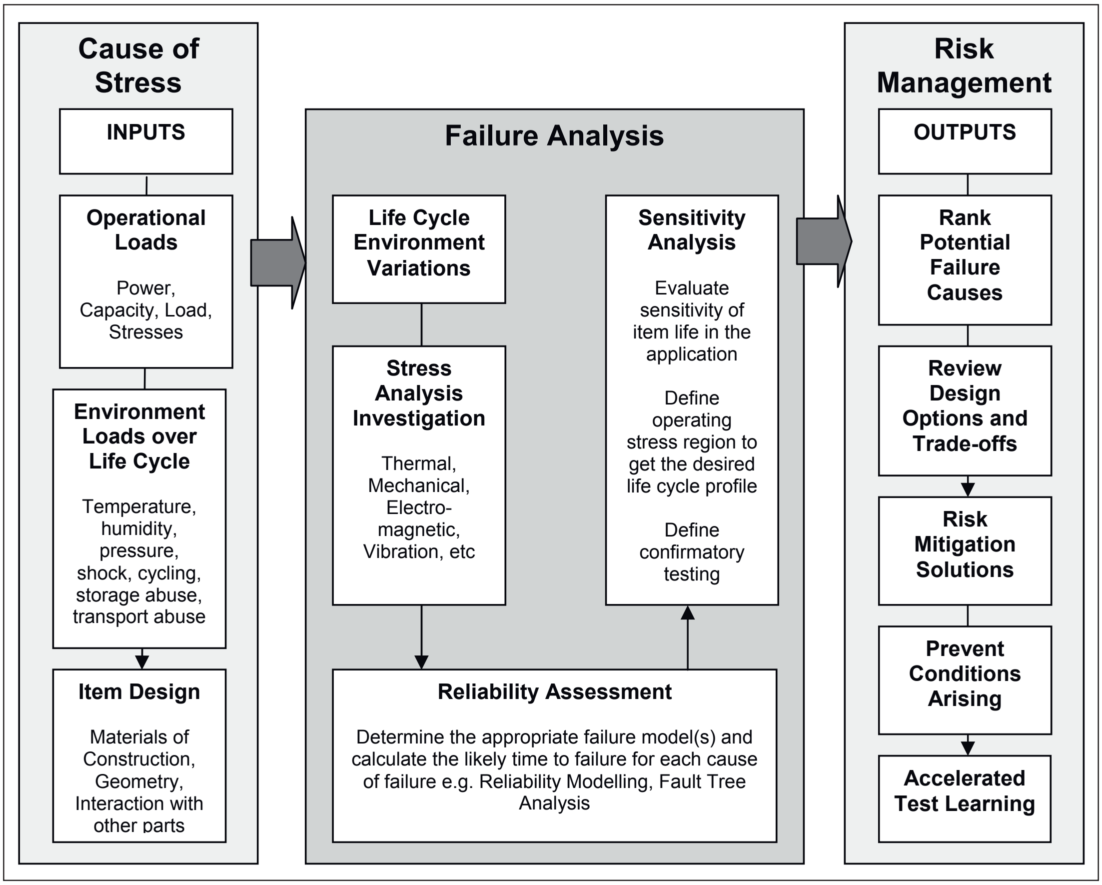

Figure 2.5 – Physics of Failure Approach to Reliability Improvement.

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.

[8] 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 [9]. 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 [10]. Once the material of construction is damaged, even normal operating loads maybe 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.

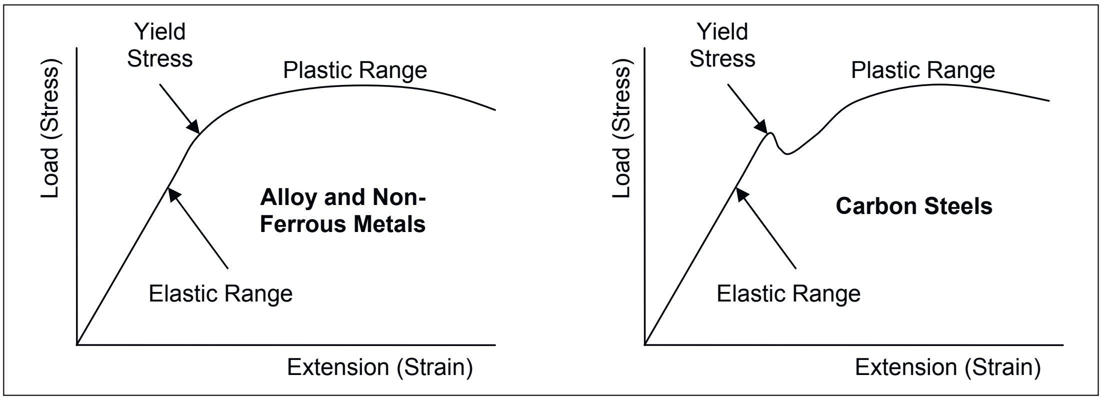

Figure 2.6 – When Metals and Materials Reach Load Limits They Deform.

There has been a great deal of fatigue load testing done with many materials. These tests produce graphs of tensile strength verses number of cycles to failure. They help us to understand how much load a material can repeatable 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

[9] Gordon, J. E., The New Science of Strong Materials or Why You Don't Fall Through the Floor, Penguin Books, Second Edition, 1976.

[10] 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.

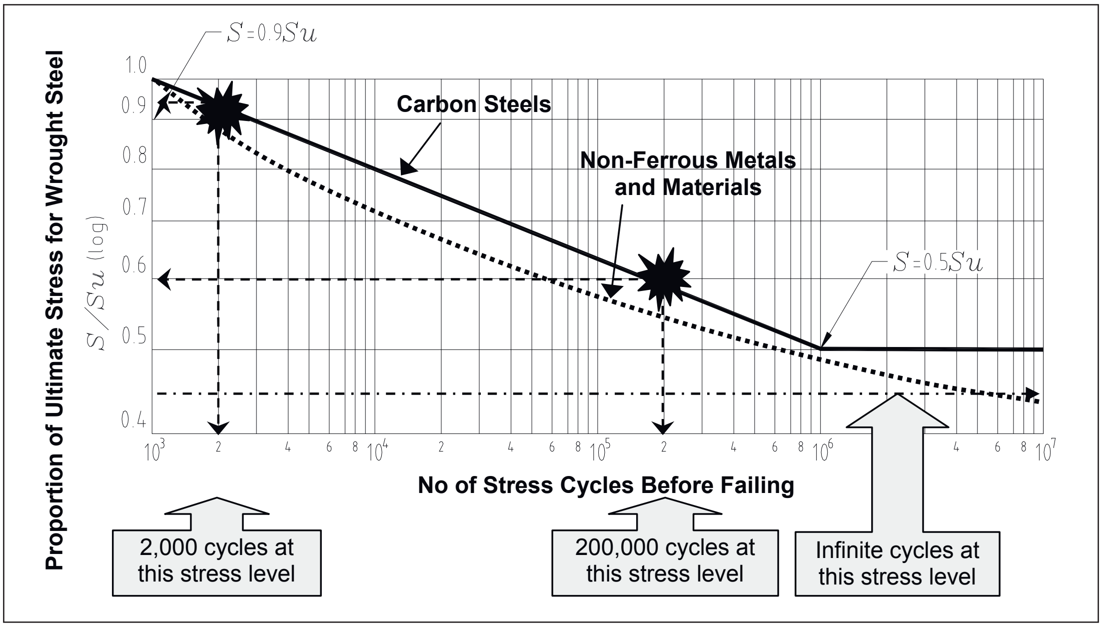

Figure 2.7 – Repeated Over-Stressing Causes Fatigue and Failure.

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.

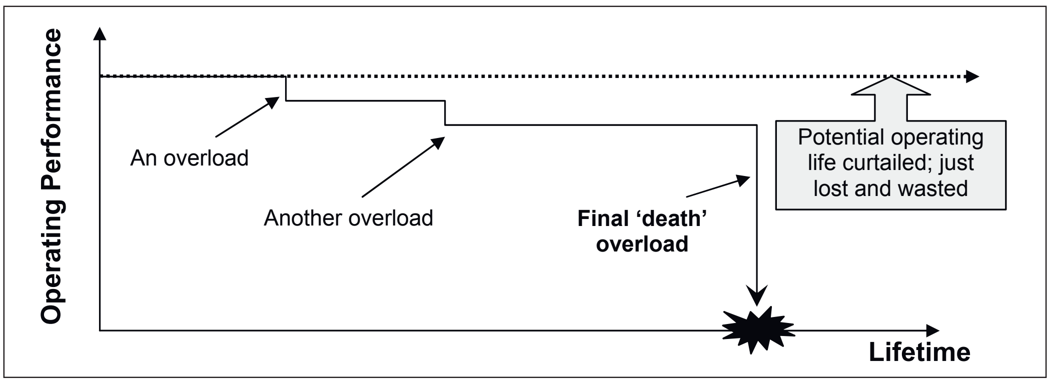

Figure 2.8 – The Stress-Driven Failure Degradation Sequence.

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.

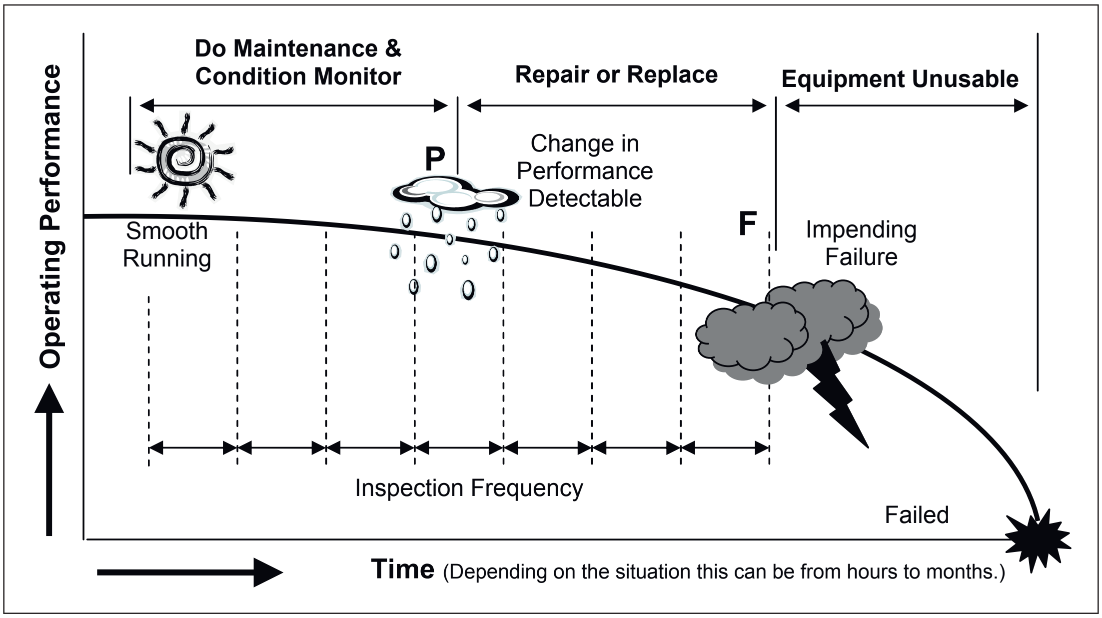

Figure 2.9 – The Fatigue-Driven Failure Degradation Sequence.

The point at which degradation is first possible to detect is the potential failure point [11], '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.

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[11] 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 [12]. 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^{o} 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.

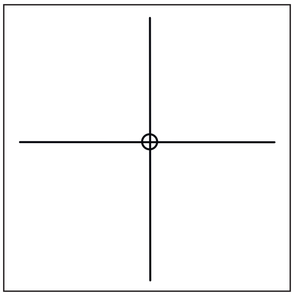

Figure 3.1 – The Cross-Hair Game.

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.

[12] 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
			Average	X = 3.48	Y = 8.90			
			Spread	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
			Average	3.82	3.87			
			Spread	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.

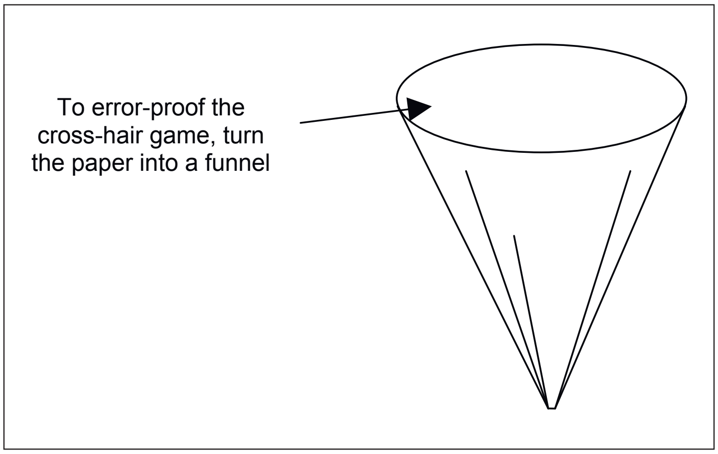

Figure 3.2 – Error-Proofing the Cross-hair Game.

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 purse excellence in their activities will not last [13].

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

[13] 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 [14]. 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.

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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[14] 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												
120N	9	1	1	1		2											1			3			

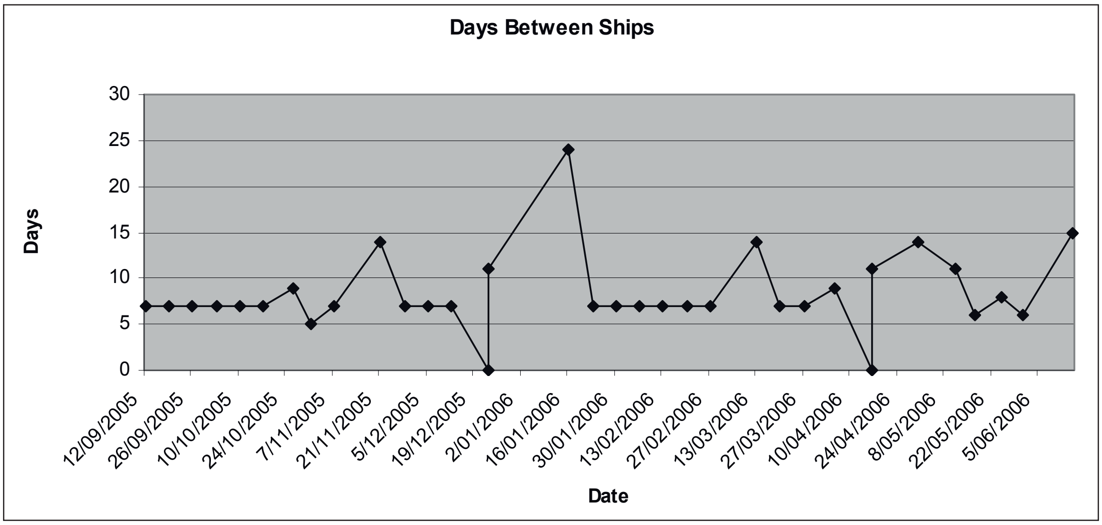

Figure E3.1.1 – Ship Departure Dates.

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.

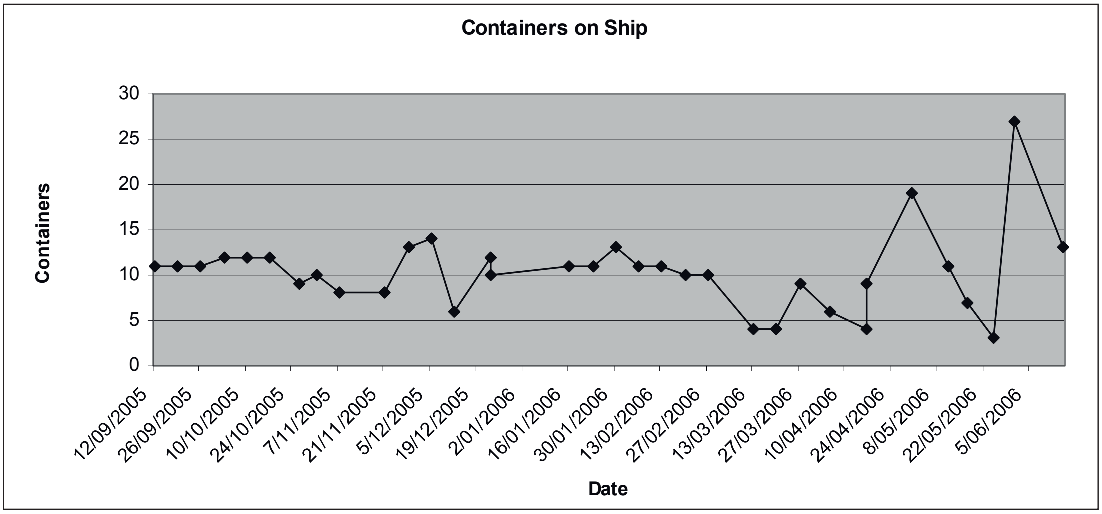

Figure E3.1.2 – Numbers of Containers on Each Ship.

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 ± 25mm 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 ± 25mm 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 [15]. The method that produces the greatest variation, ranging ± 35%, is 'Feel – Operator Judgement', where muscle tension is used to gauge fastener extension. Even using a torque wrench has a variation of ± 25%, unless special practices are followed that can reduce it to ± 15%.

It is impossible to guarantee accuracy when tightening fasteners by muscular feel. Using a process that ranges ± 35% to get within ± 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

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[15] 'Fastener Handbook – Bolt Products', Page 48, Ajax Fasteners, Victoria, Australia, 1999 edition.

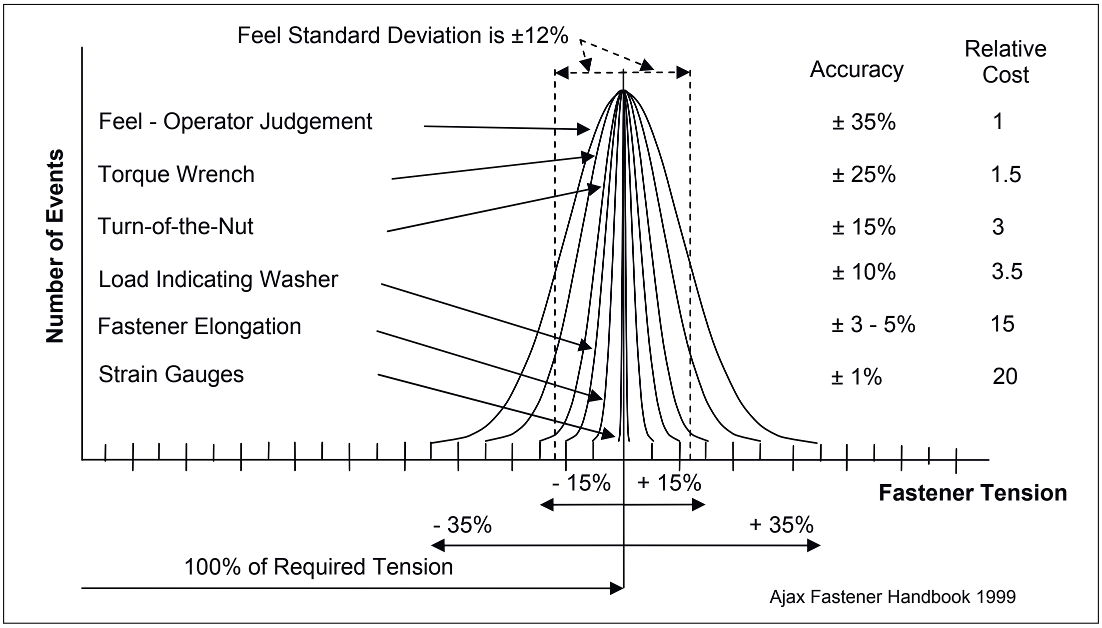

Figure 3.3 – Variability in Methods of Providing the Correct Torque for Fasteners.

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 [16] to 5 micron. Eighty percent of lubricant contamination is

[16] Jones, William R. Jr., Jansen ,Mark J., 'Lubrication for Space Applications', NASA, 2005.

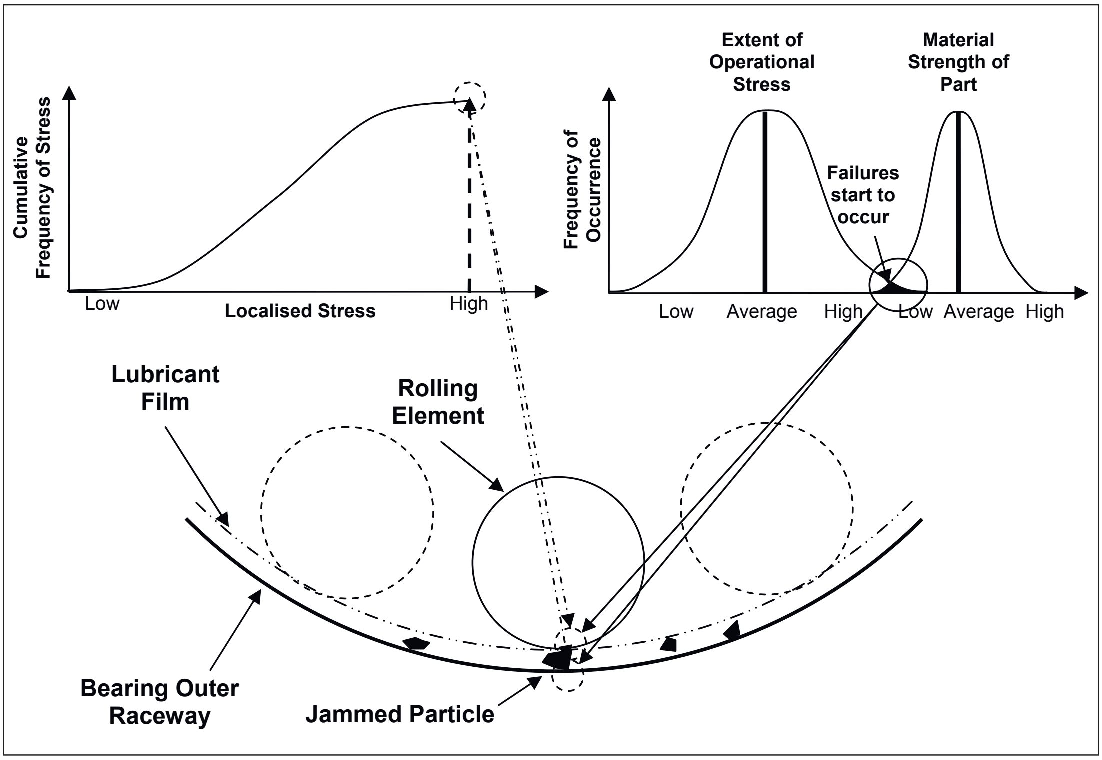

Figure 3.4 – Particle Contaminant Caught between Roller and Race Causes Overload Stresses.

of particles less than 5 micron size [17]. 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 [18]. 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.

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[17] Bisset, Wayne, 'Management of Particulate Contamination in Lubrication Systems' Presentation, IMRt Lubrication and Condition Monitoring Forum, Melbourne, Australia, October 2008.

[18] 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 [19]. Table 3.1 lists some ISO 4406 oil contamination range numbers [20]. 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

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

20 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.

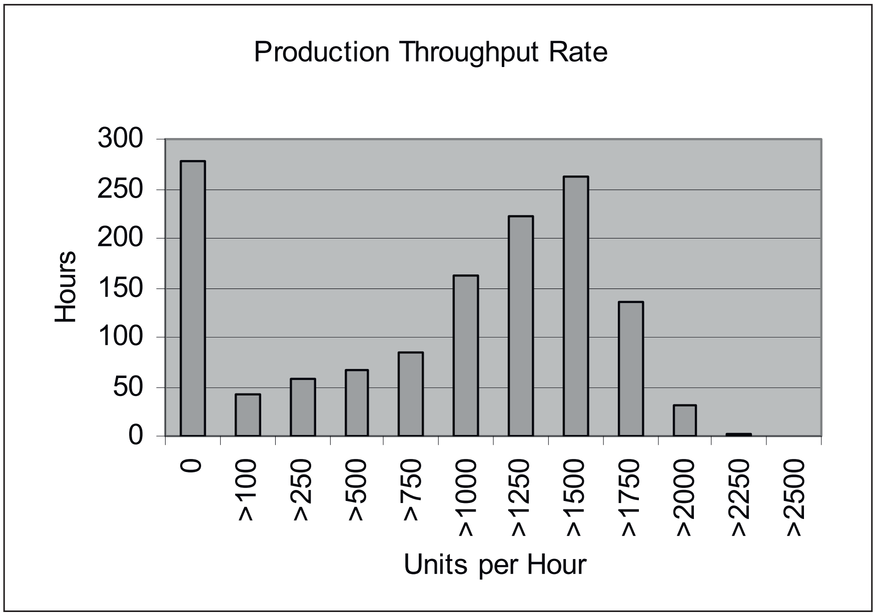

Figure E3.2.1 – Production Rates.

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

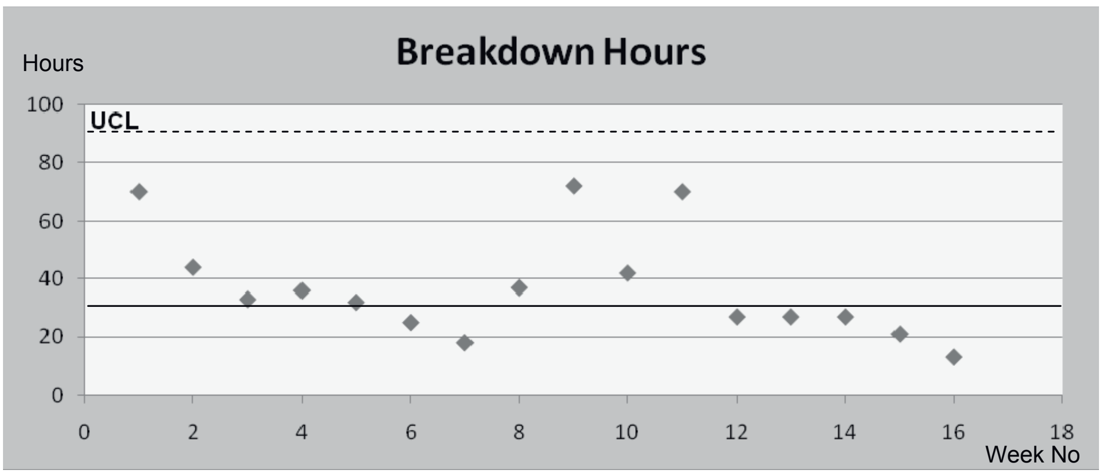

Figure 3.5 – Breakdown Hours per Week.

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 [21]. 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

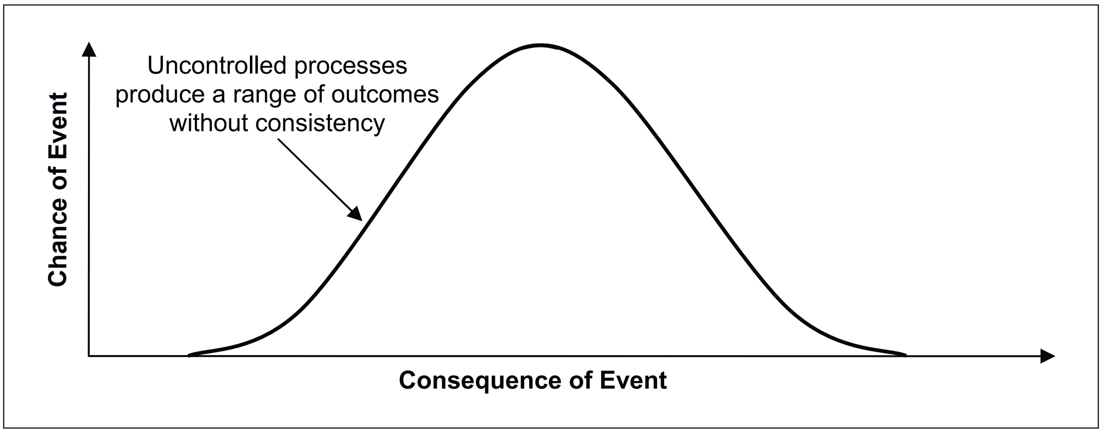

Figure 3.6 – Uncontrolled Processes Produce All Sorts of Results.

[21] Many real-world processes are normally distributed, but distributions can also be skewed or multi-peaked.

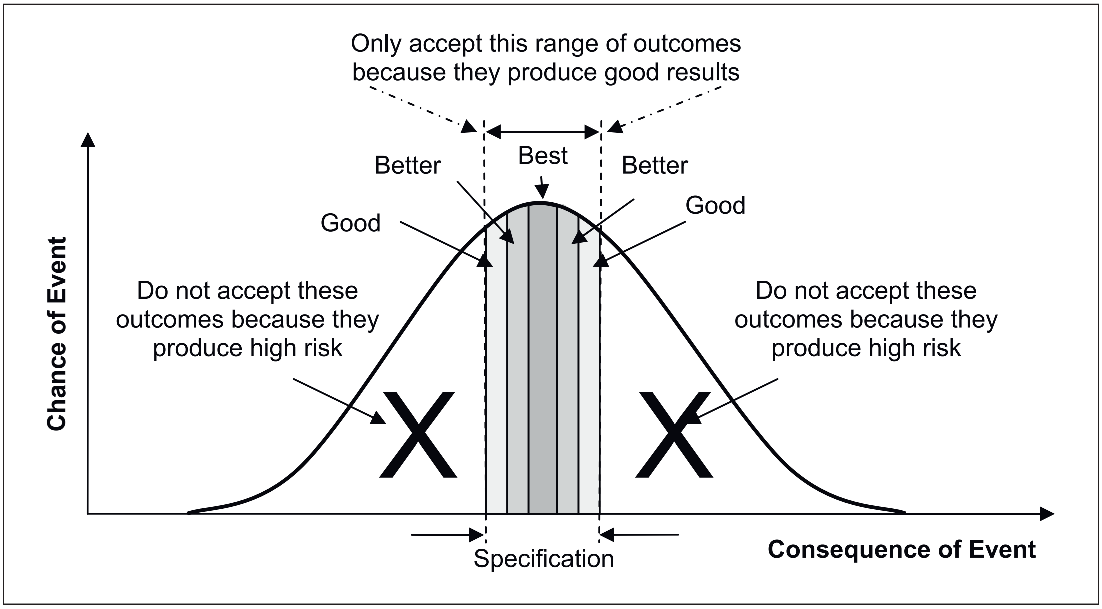

Figure 3.7 – Controlling the Chance of a Failure Event.

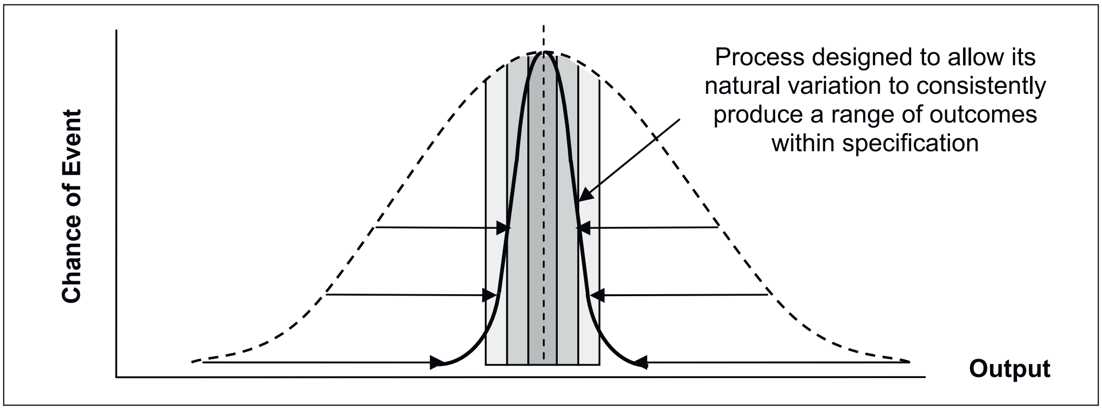

Figure 3.8 – The Effect of Removing Volatility from Business Processes.

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” [22]. Quality, Deming tells us, is installed at the source. It is designed in and made part

[22] 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.

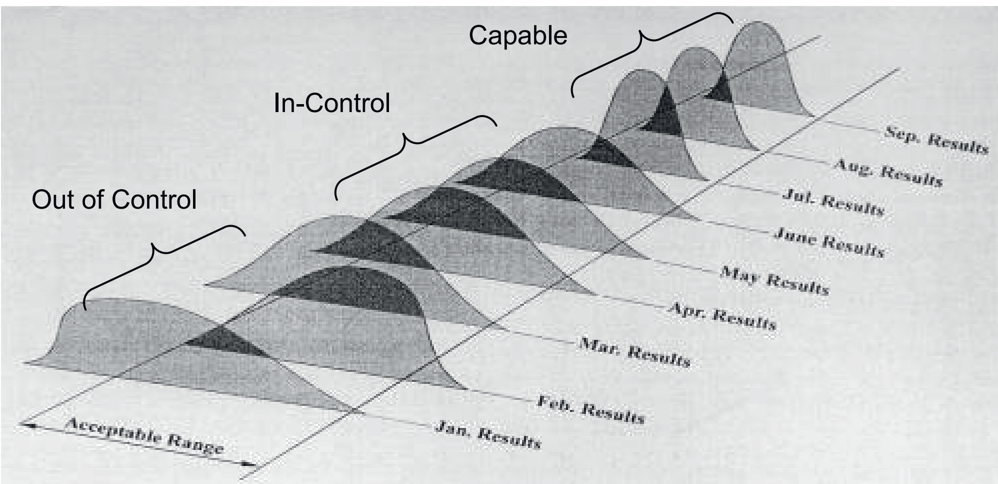

Figure 3.9 – Making a Process In-Control and Capable.

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 [23]. 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 [24]. The temperatures at which bearings operate change their internal clearances, which directly influence the likelihood of roller bearing failure [25]. 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 [26]. 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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23 Piotrowski, John, Shaft Alignment Handbook, 3rd Edition, CRC Press, 2007.

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

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

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

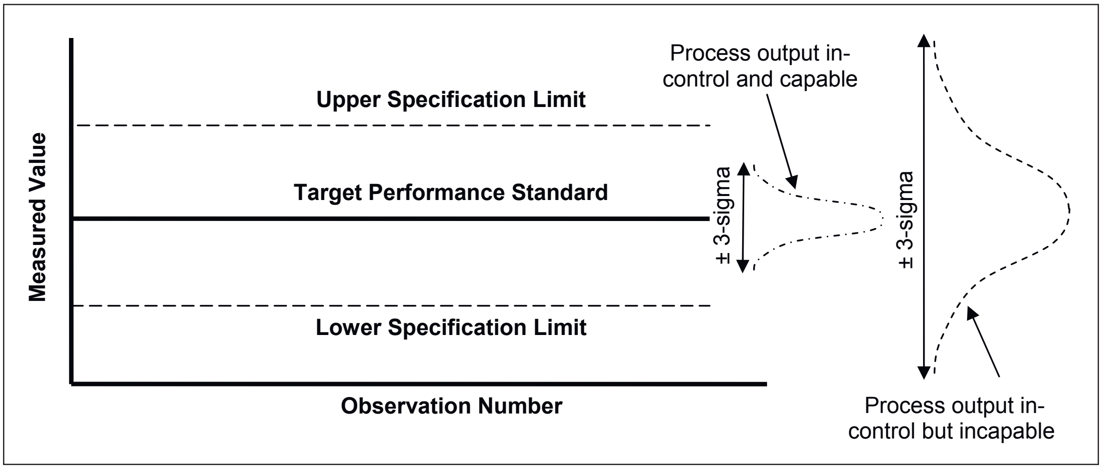


Figure 3.10 – A Basic Control Chart.

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 [27].

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 [28].

[27] Gygi, Craig et al., 'Six Sigma for Dummies', Wiley Publishing, 2005.
[28] Block, H P., Hernu M., 'Performance Benchmarking Update; expectations and reality', Gulf Publishing Company, 2007.

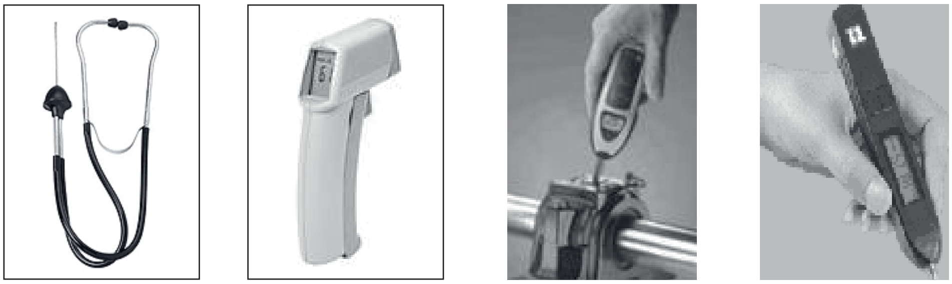
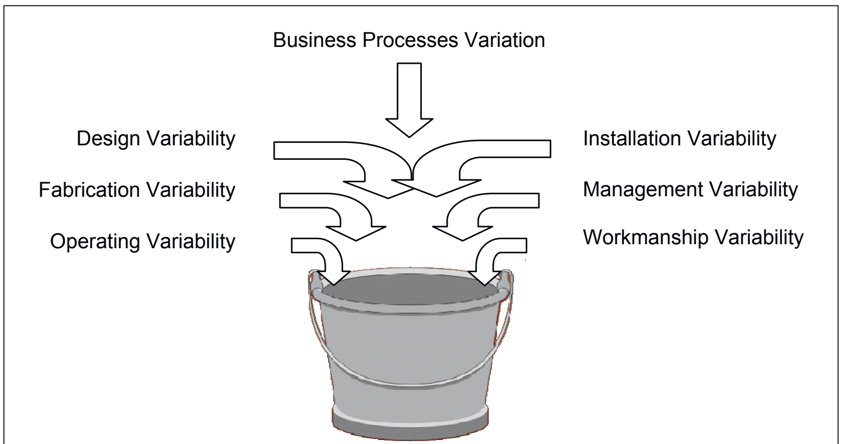


Figure 3.11 – Stethoscope Laser Thermometer Touch Thermometer Vibration Pen.

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 [29]. It highlights some of the many processes where failure causing defects and errors enter an operation.



Your operation is a bucket for collecting defects.

Figure 3.12 – Defect Creation.

[29] Ledet, Winston J., 'Engaging the Entire Organisation in Improving Reliability', The Manufacturing Game™, Atlanta, Georgia, USA.

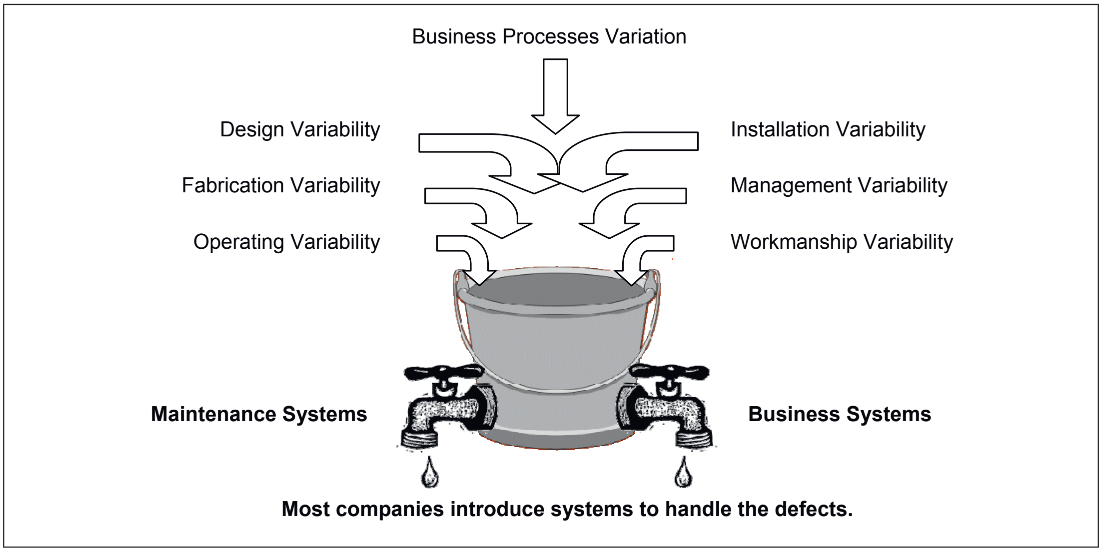


Figure 3.13 – Defect Management.

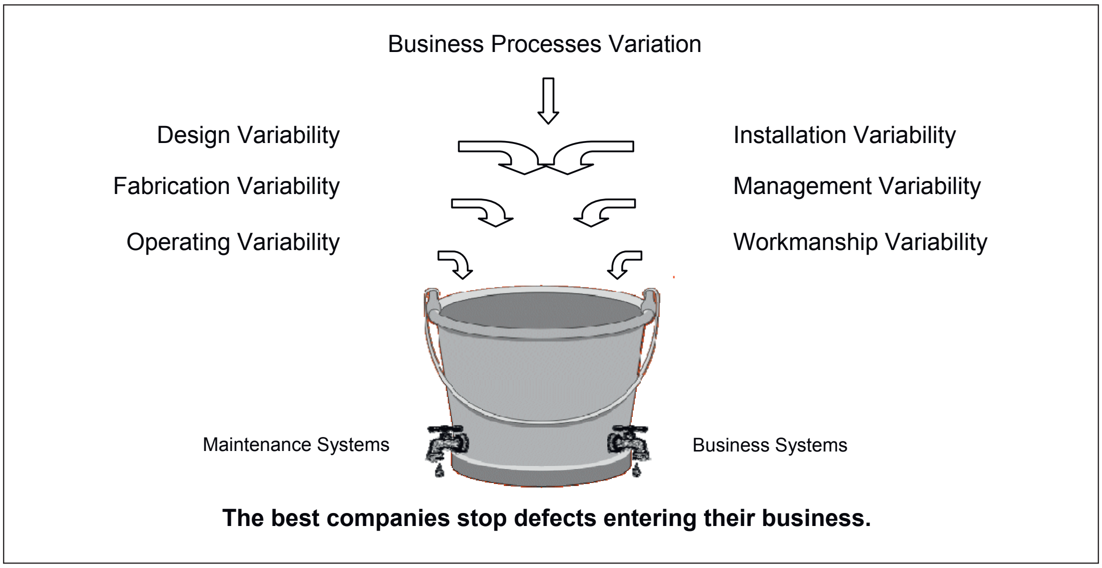


Figure 3.14 – Defect Elimination.

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.

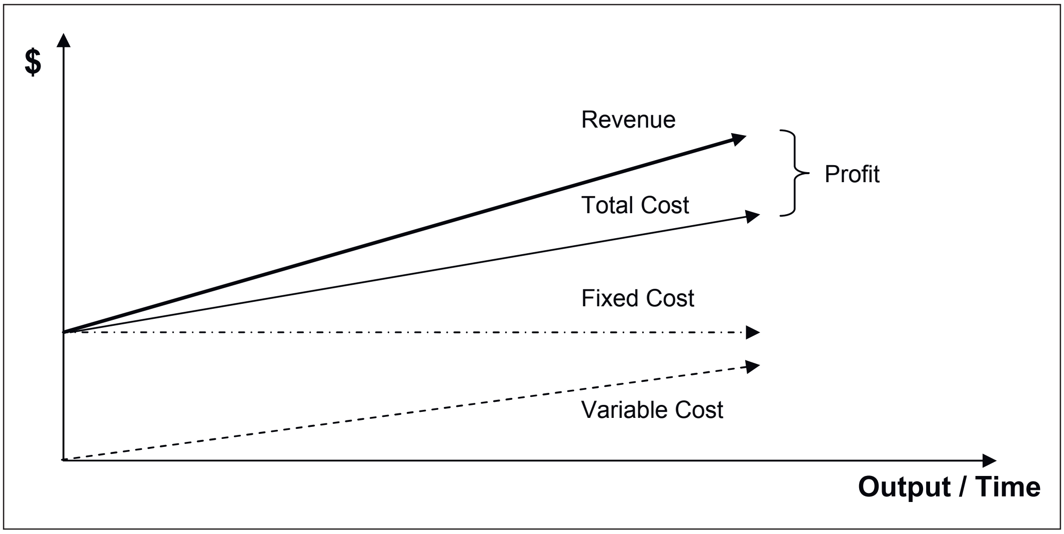


Figure 4.1 – Costs during Normal Business Operations.

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.

Profit ($) = Revenue ($) – Total Costs ($) *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.

Total Costs ($) = Fixed Costs ($) + Variable Costs ($) *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.

Total Costs ($) = Fixed Costs ($) + Variable Costs ($) + Cost of Loss ($) *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.

Cost of Loss ($/yr) = **Frequency of Loss Event** (/yr) x **Cost of Occurrence** ($) *Eq. 4.4*

Risk ($/yr) = **Frequency of Event** (/yr) x **Consequence of Occurrence** ($) *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.

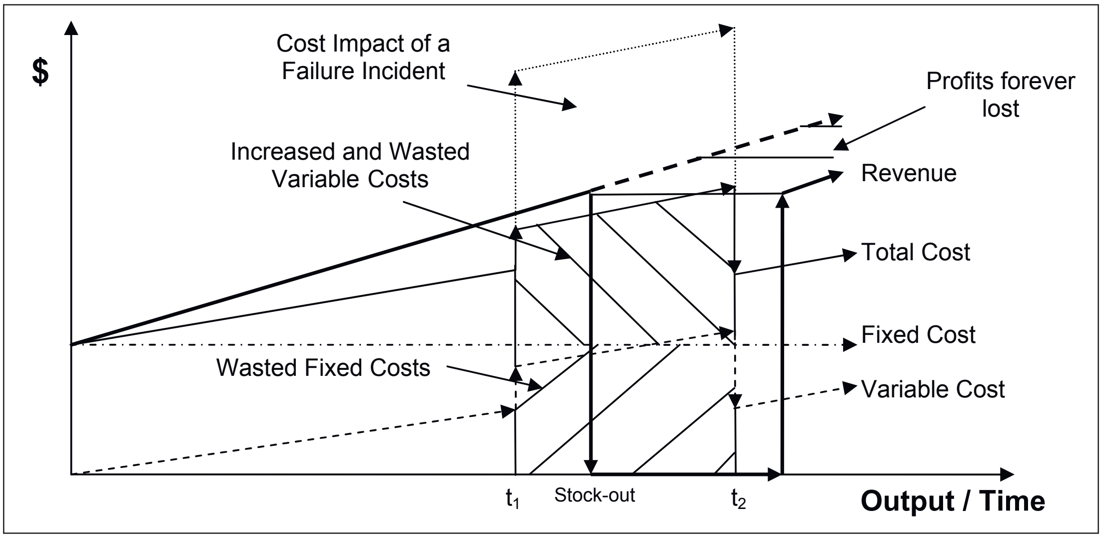


Figure 4.2 – Effects on Costs and Profit of a Failure Incident.

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'.

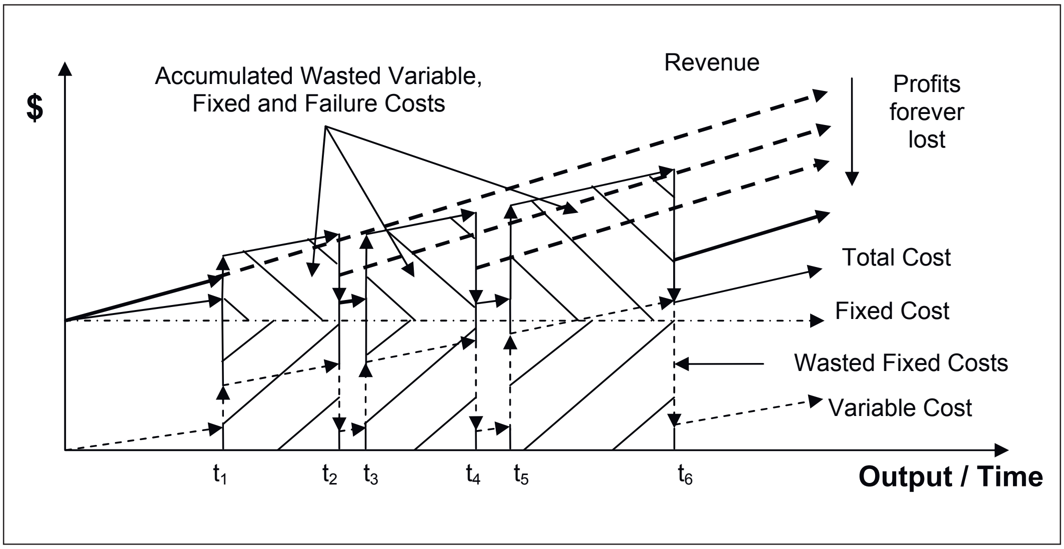


Figure 4.3 – Effects on Profitability of Repeated Failure Incidents (Death of Many Cuts).

The true cost of failure to a business is far bigger that simply the time, resources and money that goes into the repair. Failures and stoppages are the number one enemy in running a profitable operation. They have a cumulative impact on the operation's financial performance. With too many failures or downtime incidents a business becomes unprofitable. The money spent to fix failures and to pay for the wasted costs leaves only poor operating profits behind.

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.

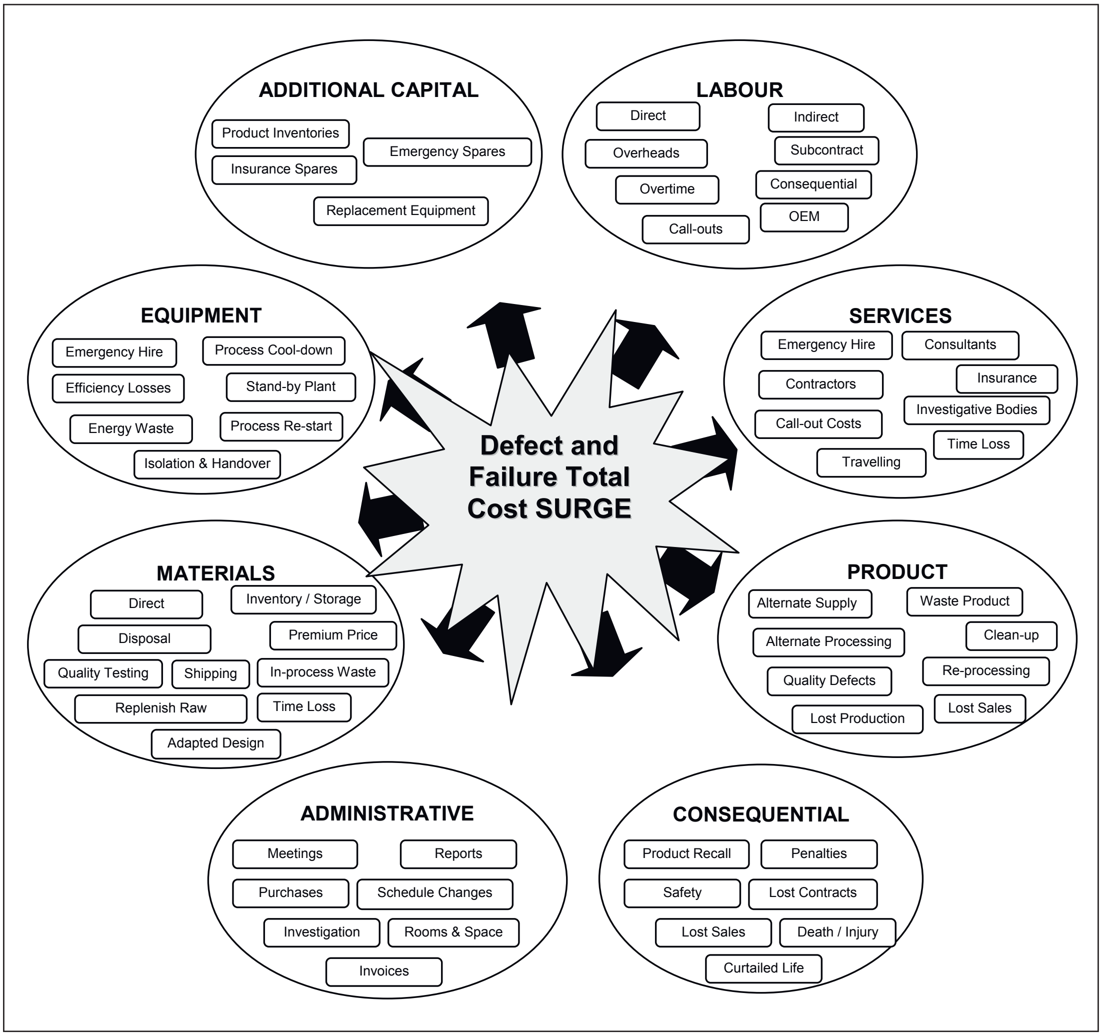


Figure 4.4 – A Multitude of Costs Arise and Profits are Lost Due to Defects and Failures.

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.

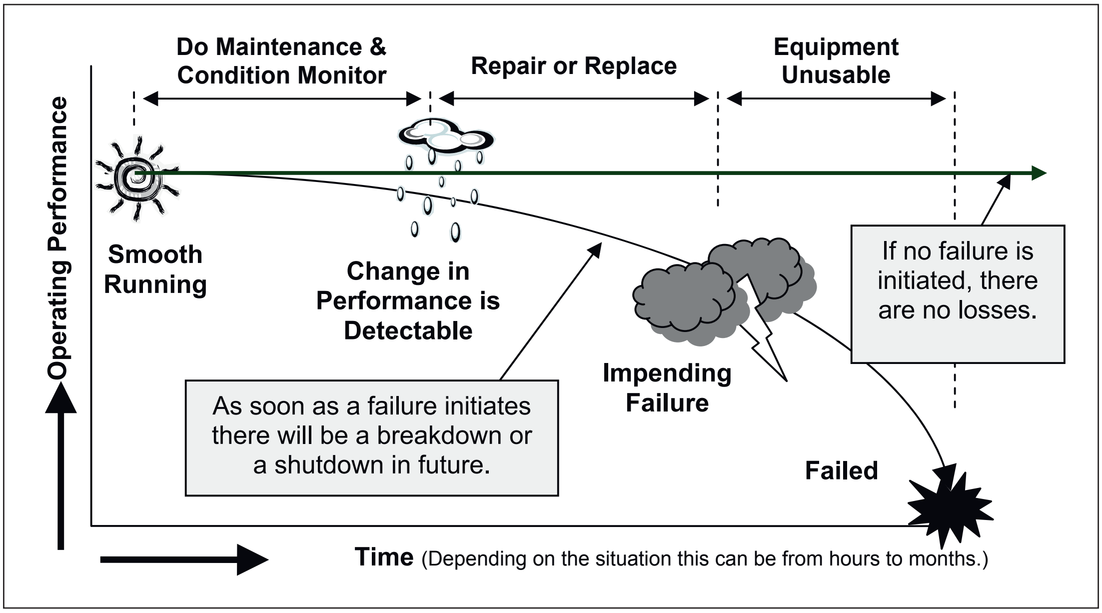


Figure 4.5 – Failure Starts Well Before it is Observable.

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	
13	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 to 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	
	TOTAL	**755**	**$970**	**$350**

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
	TOTAL OF EXTRA COSTS		**$2,018**	**$32,905**

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
2. Gather Costs
3. Trace Costs to Activities
4. Analyse Costs
5. Finalise Costs and Report

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					
Administration		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.

Purchased Material's and Service's Costs Incurred Because of a Failure Incident					
Department	**Department Process Affected**	**Plant, Equipment and Machinery Affected**	**Parts, Materials, Services Purchased**	**Total Invoiced Purchases**	**Total Labour Costs**
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		
TOTAL COST					

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.

Material's and Product's Waste Costs Incurred Because of a Failure Incident						
Department	**Dept Process Affected**	**Plant, Equip and Machinery Affected**	**Materials, Products Wasted or Reworked**	**Unit Cost of Waste and Rework**	**Total Wasted / Reworked Units**	**Total Waste Costs**
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				
TOTAL COST						

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			
TOTAL COST					

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.

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

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.

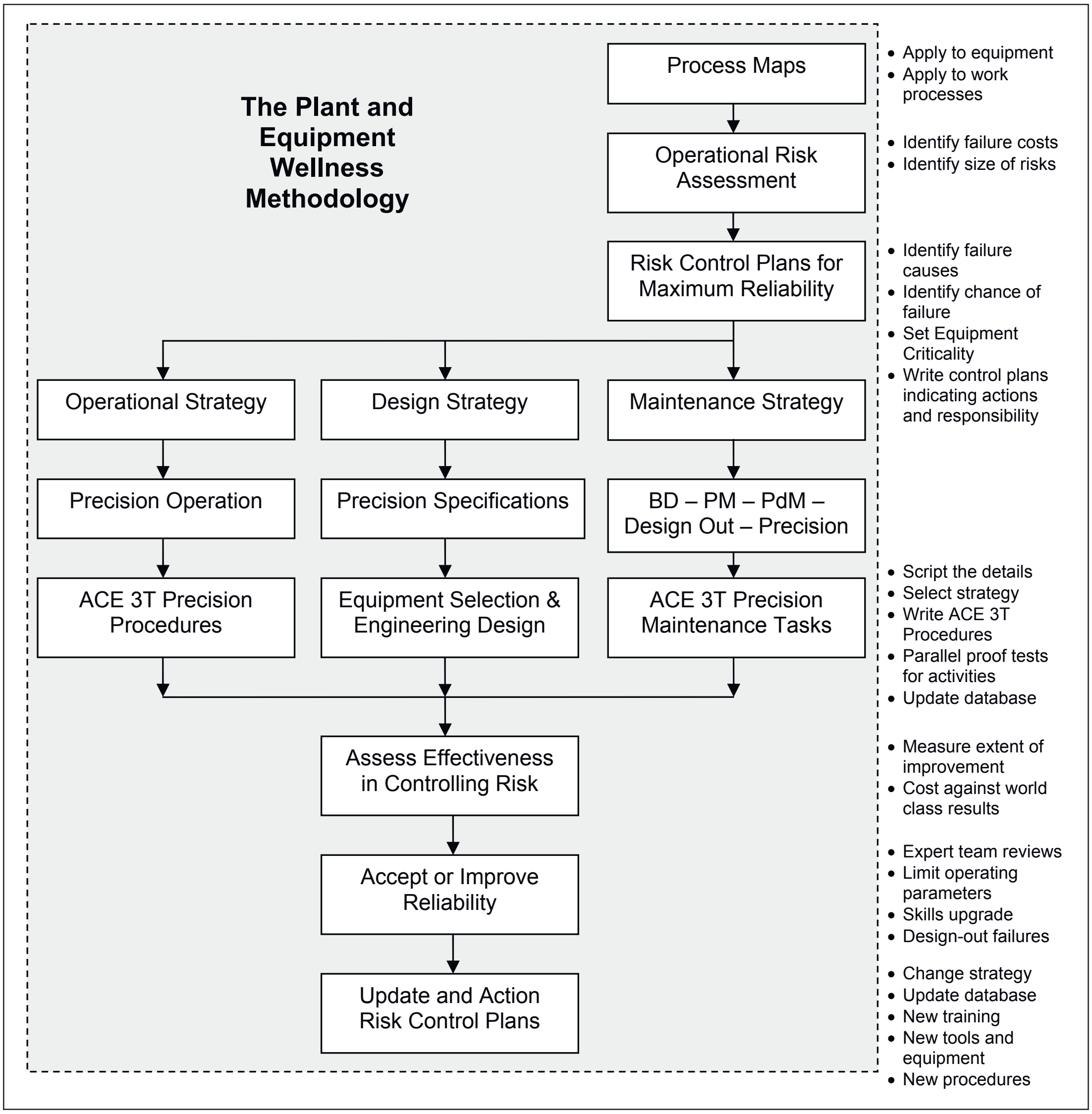


Figure 5.1 – Controlling Operating Risk with the Plant and Equipment Wellness Methodology.

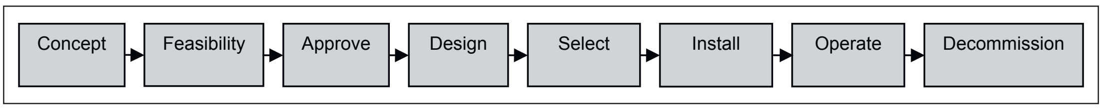


Figure 5.2 – A Process Map of the Equipment Life Cycle.

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.

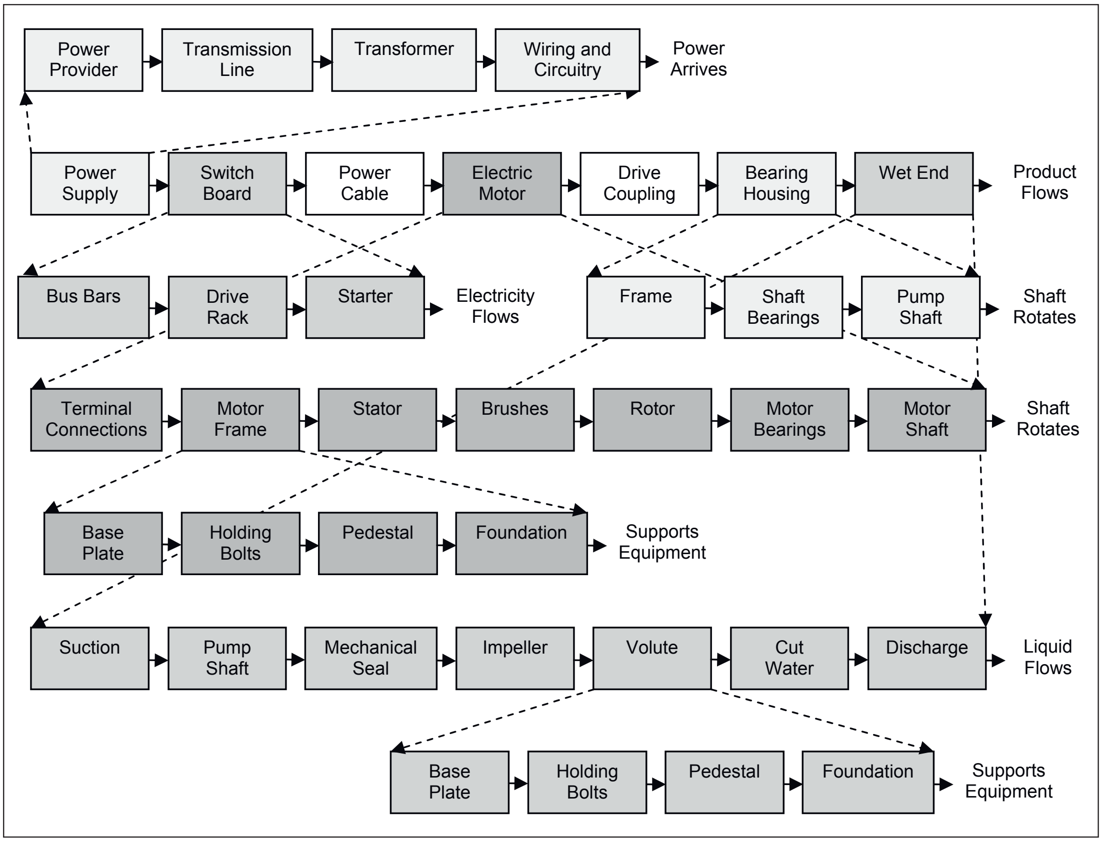


Figure 5.3 – A Process Map of a Centrifugal Pump-set Delivering Product.

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 though 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 [30]. 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. Lightening 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					

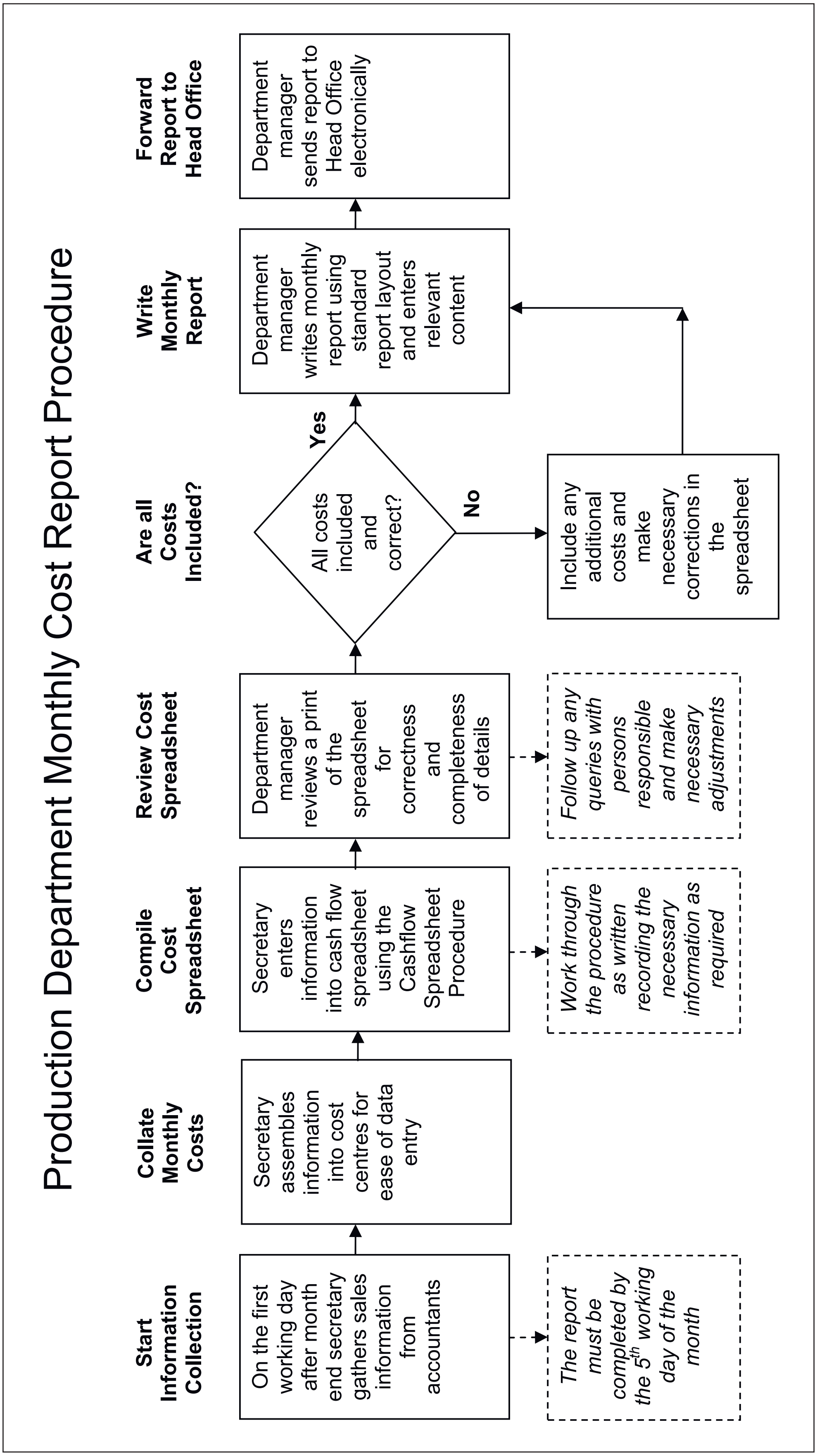


Figure 5.4 – A Job Procedure Converted into a Work Process Map.

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' [31] – "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."

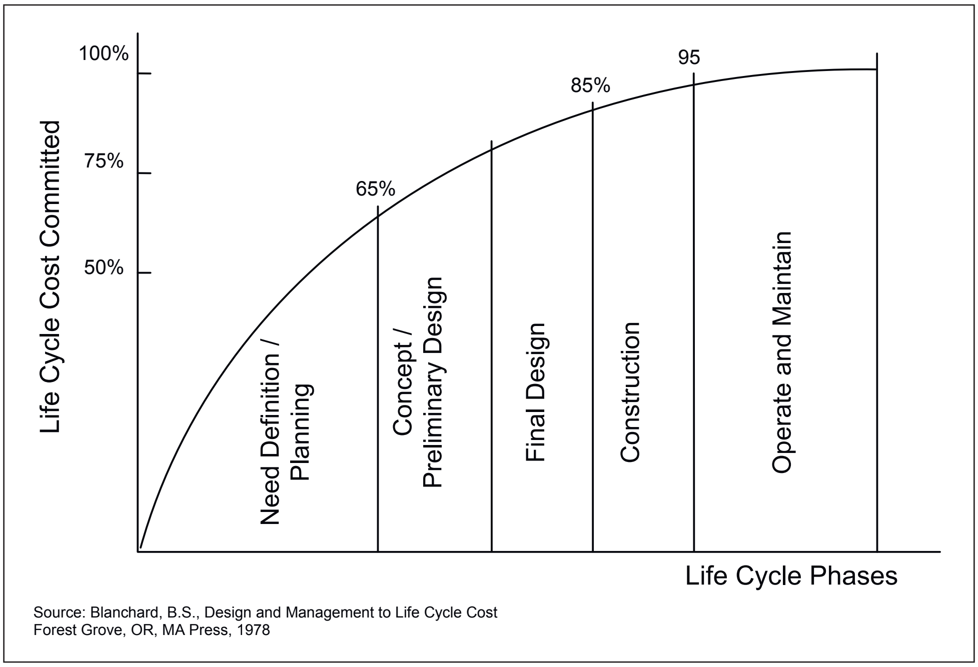


Figure 5.5 – Life Cycle Cost Commitments.

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.

[30] Source: Blanchard, B.S., 'Design and Management to Life Cycle Cost', Forest Grove, OR, MA Press, 1978.
[31] 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						

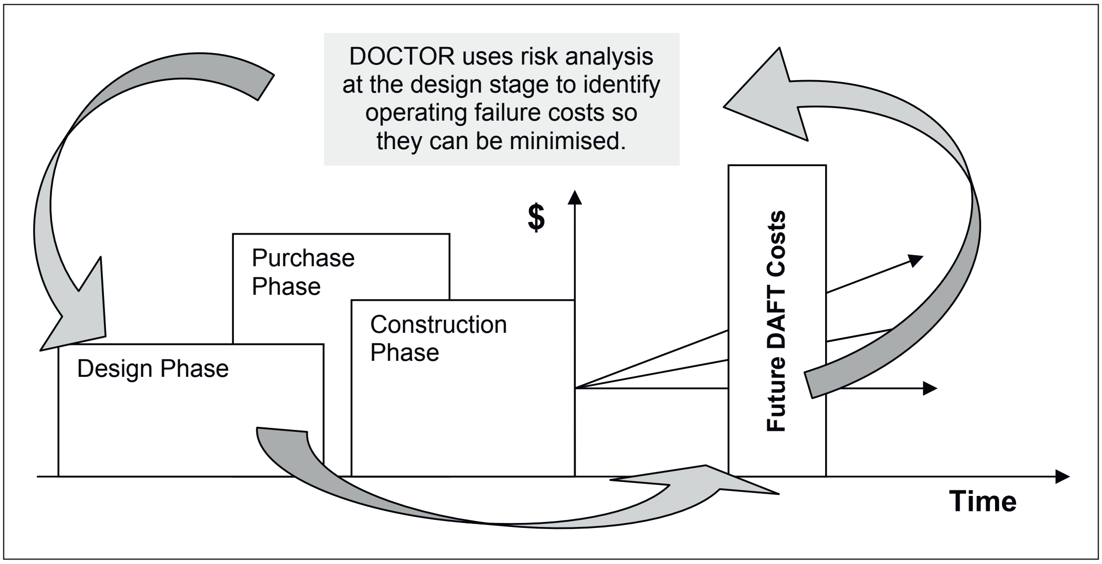


Figure 5.6 – DOCTOR uses Future Operating Costs to Prevent Operating Risks at Design.

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.

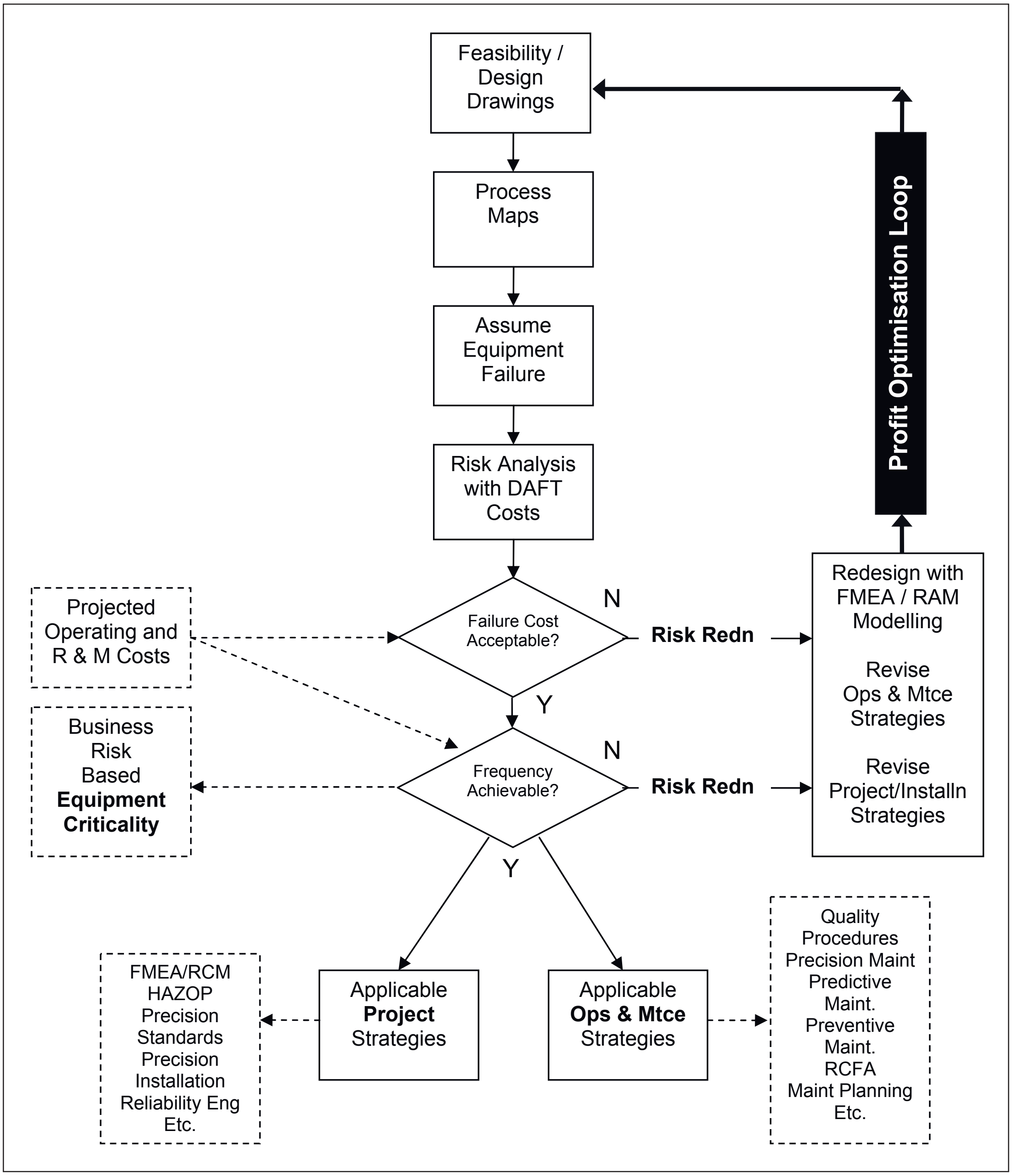


Figure 5.7 – Optimised-Profit Operating Risk Management Design Methodology.

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.