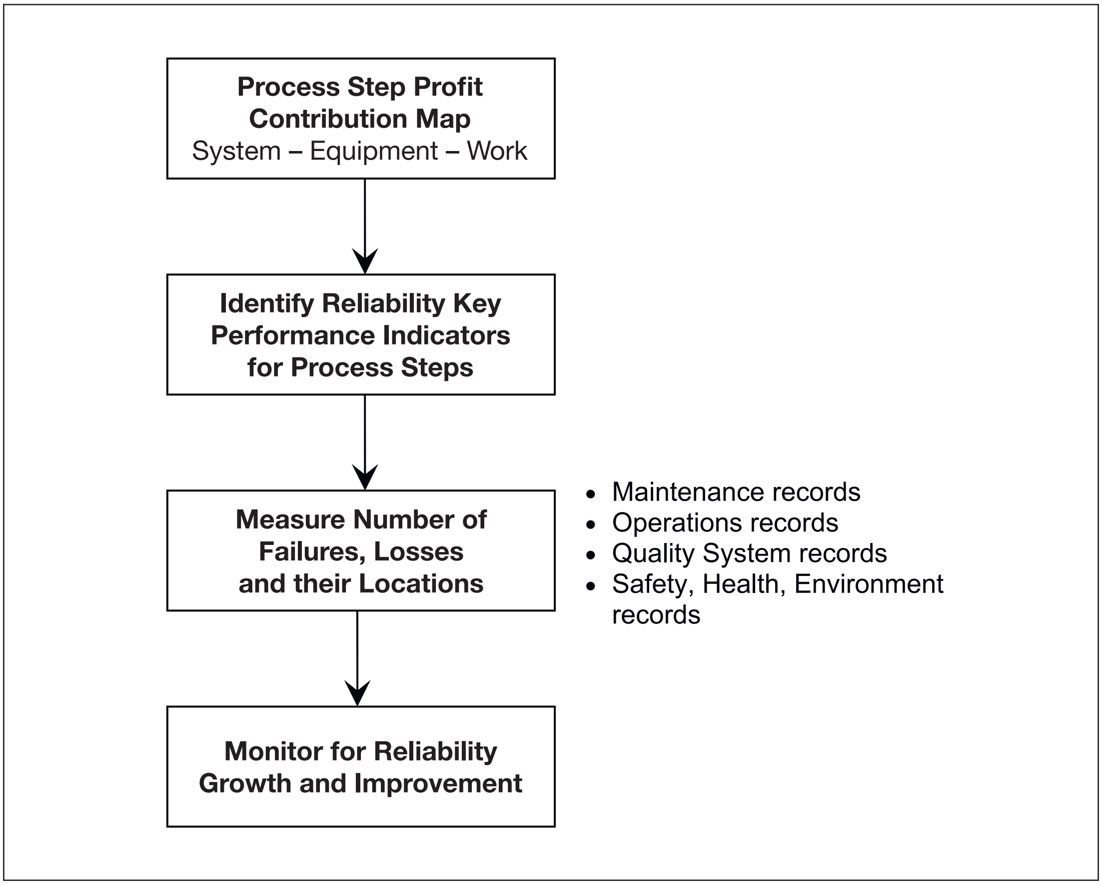
PROCESS 5 – Operating Risk Monitoring and Measuring



Description of Process 5 – Operating Risk Monitoring and Measuring

Good maintenance is a foundation requirement for good production, that is why Total Productive Maintenance had to be developed before Just in Time production could work for Toyota of Japan. It means that world-class maintenance is a foundation requirement for world-class production. They are supportive partners. Maintenance provides plant and equipment able to run at design duty, ensures machines are fit to make 100% quality product, and keeps equipment safe so it does no harm. To measure the business success of maintenance it is necessary to measure the profit it makes through the savings it contributes.

Process Step Profit Contribution Map

Process maps are used to identify how to make a process more efficient. At each process step inputs are added and outputs are produced. Process Step Contribution Mapping lets you calculate the financial value added in a step. With detailed knowledge of step contributions and losses it becomes clear what to do to improve efficiency and effectiveness.

Key Performance Indicators

Key Performance Indicators are required at the process step level and for the whole process. Those at the step level are used by the people doing the work to spot loss and waste. Those at the process level are for the people responsible for the operation to optimise the process and maximise profit.

Measure Failures and Losses

Measure production downtime and process step wastes/losses to ensure that the maintenance and production efforts reduce them. Successful maintenance prevents equipment failures and minimises production losses. It does that by keeping plant and equipment fit and in good health. Well plant and equipment costs less to operate while making quality production to schedule.

Monitor for Reliability Growth and Improvement

The results of improvement efforts need to lead to improvement. Show people how things are performing with visual diagrams, charts and graphs. When the performance is not what is wanted, team-up with people and plan what to do about it, then action the plan to test if the ideas solve the problems.

Use Key Performance Indicators to track the direction and progress made. Correct and improve those activities not yet performing well enough with the help of the people doing them by using the 'Change To Win' improvement program accompanying this book.

15. Process Step Profit Contribution Mapping

Plant and Equipment Wellness is as much about the wise use of money as it is about the wise use of engineering, maintenance and operational management to deliver top performance from production equipment and processes. Maintenance provides equipment reliability and reduces operational risk. It can also cut production costs if targeted on reducing production wastes by ensuring equipment and operating plant work efficiently. The higher you keep the process efficiency, the smaller are your losses, and the more profit you make. You need to know the size and location of your losses in order to target maintenance on improving the plant and process efficiency.

Process Step Contribution is a financial diagnostic tool used to produce key performance indicators of process efficiency. It provides a snapshot of the money flows in and out of a process step. With it you know where the wastes and losses are in your process. It is a fundamental tool for rapidly improving business profitability. Instead of waiting for financial reports delivered weeks after doing the work, Process Step Contribution maps the true costs of operating a process while it is happening. It provides accounting and cost data about each step in a process and allows identification of opportunities to improve the step's efficiency and effectiveness. Once each step's money flows are known it becomes clear where there are excesses and waste. Knowing the money made and lost permits focused and targeted process improvement and re-engineering to minimise wastes and losses.

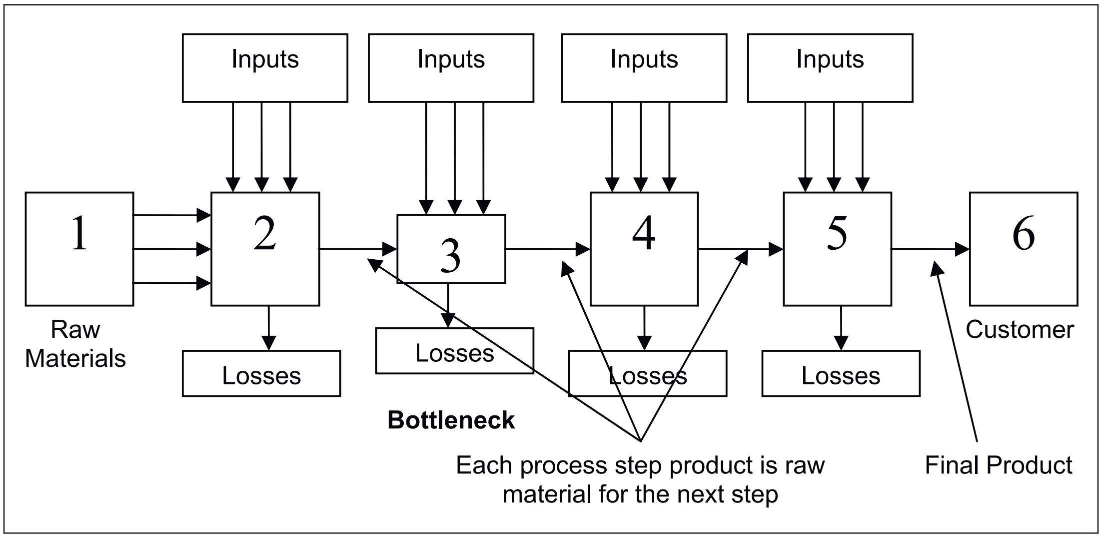


Figure 15.1 – A Business Conversion Process.

Process Step Contribution Mapping derives from the Toyota Production System value stream mapping. Whereas value stream mapping focuses on identifying the seven wastes in a process [69], Process Step Contribution Mapping focuses on the financial gains and losses happening in every process step. The power of Process Step Contribution Mapping is its ability to identify exactly where every dollar goes in a business. Organisations examine the financial performance of their departments, but few businesses establish financial data collection on what actually happens within their processes. Preferring instead to employ supervisors and managers to control and direct the operation and get delayed results on actual performance.

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[69] Liker, Jeffery K., 'The Toyota Way 14 Management Principles from the World's Greatest Manufacturer', McGraw Hill, 2004.

Application of Process Step Contribution Mapping employs cost accounting and activity based costing practices to accurately identify money movements throughout the steps of a process. The money movements in each process step are modelled using basic accountancy equations. Once the equations for each process step are developed, Process Step Contribution Mapping uses the financial information and data already available in the business to snapshot what is happening. The cost equations reflect the money flows in a step and their development requires engineering precision to capture every cost and waste. By understanding the money flows in a process step it becomes possible to identify improvements and better practices to optimise that step, and so make the whole process more productive and profitable.

Figure 15.1 is a symbolic production, manufacturing or service process showing a series of numbered boxes for each conversion step. The materials, utilities, services and labour flows are represented by arrows.

Production, processing and manufacturing systems turn raw materials into finished products through a series of steps that progressively convert them into saleable products. Typically, a conversion process takes raw materials and adds inputs such as labour, utilities, (like power and water), specialist services, (like engineering and maintenance), supplementary materials, (like boxes for packaging) along with other necessary requirements to make products customers buy. Maximising profit requires both efficiency and effectiveness from every step.

An effective process makes and delivers what the customer wants. An efficient process delivers the profit the shareholders want. An important job for managers, economists, accountants and engineers is to develop business systems that reliably achieve seamless operation to the benefit of the organisation, its customers and community. This requires on-going commitment to continually improve and tune the organisation to be more efficient and work faster, better and cheaper.

Properties of Production Processes

In Figure 15.1 raw materials and added inputs enter each step. The process steps use these to add value and make the products produced by the organisation. During production the product increases in value equal to the sum of value added in each conversion step. Each value-adding step contributes part of the profit. A process step does not produce perfect conversion and some losses occur. The customer pays for those unwanted losses when they buy the product.

A production process should only make what the market will purchase. Otherwise it ties-up money in inventory that no one wants. Balanced production means buying raw material and inputs at the same rate that you sell the product. The market and business economics regulate and control the production rate and the amount of raw materials and inputs you buy. This is the essence of a market-based, capitalist economy – products made, that people want, in production systems balanced to the demand.

From Figure 15.1 we can state a few simple properties of a business process:

i. A process step adds value if the output is worth more than the sum of raw materials, inputs and losses.

ii. The customer demand rate dictates the ideal manufacturing rate.

iii. The process design establishes production efficiency and costs.

iv. Process design determines product quality.

v. The bottleneck limits the maximum throughput rate for the process.

Bottomless Pits of Losses and Waste

Process losses behave differently to anything else in the production process. Market demand does not naturally limit them. Their only limit is how much money is available to be lost in the production system. All wastes take money from what would have been profits. Because there are no systematic internal constraints on waste they are controlled by minimising them during design and by managing them to minimal levels during operation.

Usually the wastes are not seriously considered in business process design. Standard accounting and cost accounting systems do not measure them. The wastes include the obvious waste product and scrap materials commonly associated with production waste. But there are many other types of waste produced. Other wastes which are numerous and common, but not often noticed, include such things as excess movement, lost heat, lost water, lost energy, excess storage space, excess in-process inventory, excess time, lost time, quality defects, excess forklift pallet hire, excess equipment hire, safety incidents, environmental incidents, excess paperwork, excess manning, and many, many more. Figure 15.2 is a business losing profit through its wastes.

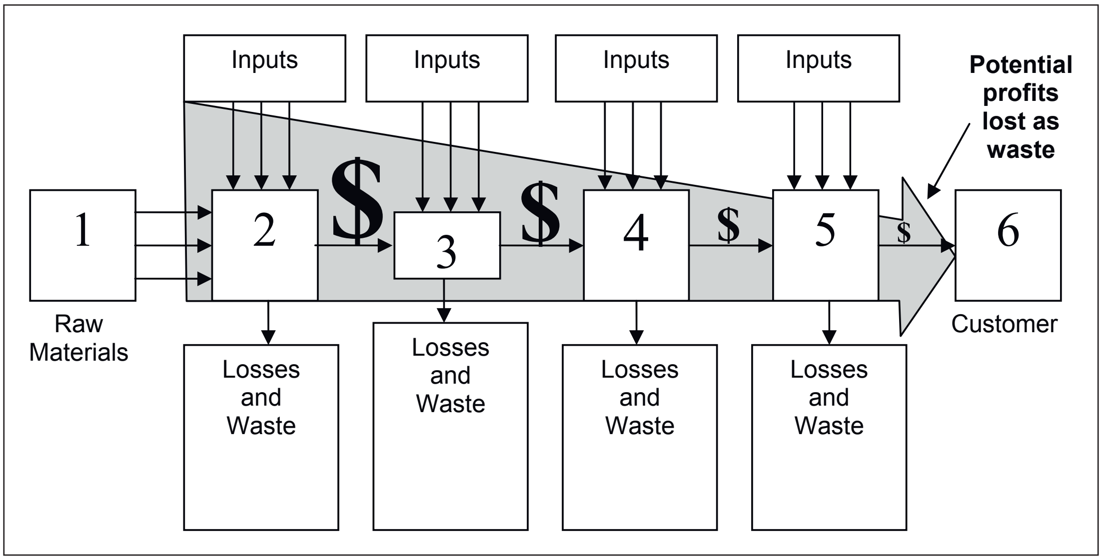

Figure 15.2 – Losses and Wastes in a Production Process.

Some of these wastes are identifiable by using value stream mapping, typically time, motion and distance, but the technique does not price lost moneys. In order to recognise the cost impact of waste it is necessary to identify their real financial loss to a business with Process Step Contribution Mapping. Waste creation has no natural means of self-control beyond bankrupting the business. Businesses need control systems that monitor the waste and force its minimisation and eventual total elimination. There are now two additional properties of a process that we can state:

vi. Wastes extract effort and profits from a process.

vii. A process can turn raw materials and inputs into waste so that the process makes waste instead of profit, to the point where waste consumes all the profits.

We can use these seven properties of a business process to understand how money behaves within it and identify the costs and wastes that reduce its performance and profit. This is Process Step Contribution Mapping. It spots all wastes and identifies all moneys lost.

Identifying Value Contribution

Once a process is operating concerns naturally turn to making the product on-time. The demand to make product on-time often overrides the need to make it cost effectively. This leads to situations where everyone is busy making product, but no one is busy making profit. If this situation occurs in an organisation the creation of waste, instead of profit, dramatically rises. Process Step Contribution Mapping helps manager, supervisors and engineers collect the cost information needed to operate a production system efficiently and effectively.

Each process step has its own raw materials fed from the prior process step. It has its own added inputs needed to make the conversion. From each step come a 'product' and the wastes. Each process step is clearly identifiable from its predecessor and its successor and is self-contained in performing its conversion. Each process step is independent of the others and is a whole system in itself. This allows us to analyse each process step separately. To make clear which process step is being reviewed draw a boundary around it on the process flow map. An example of segregating a process step for analysis is Figure 15.3.

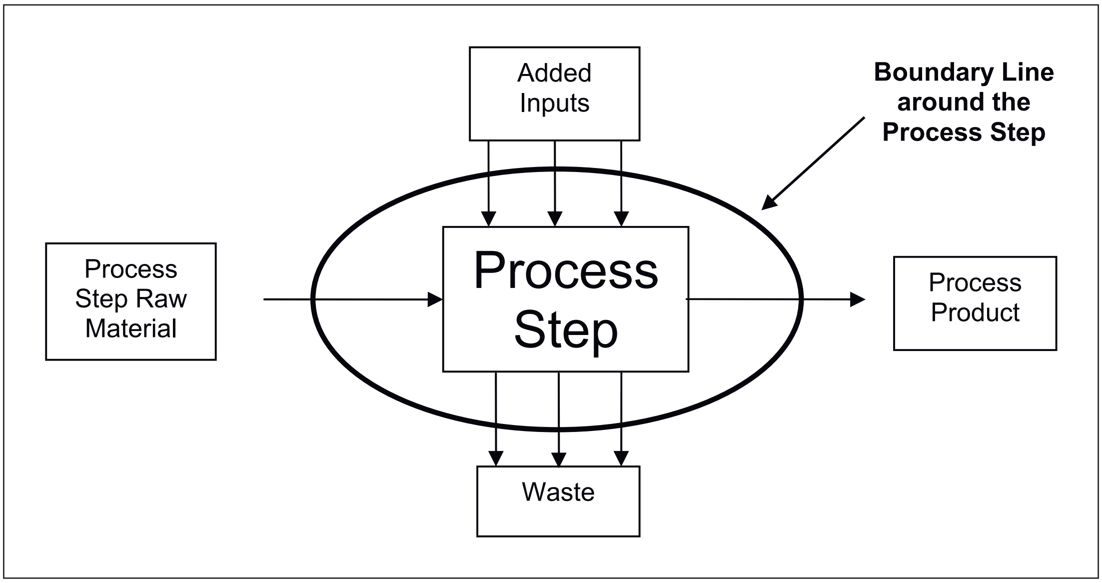

Figure 15.3 – Local Process Step Analysis.

To determine process effectiveness and efficiency we need a measure. A good measure to use in business is money. Money is the universal language of commerce and most people understand the concept of using money to value an item or service. By using money to measure a process step's raw materials, added input's cost, cost of wastes and the process step product, we can trend the step's profit contribution while making the product.

Figure 15.4 indicates the various money flows in and out of a production process. By analysing the costs of the raw materials, the costs of the additional inputs and the wastes lost from it, the contribution of a step to the final product cost can be determined. Monitoring the costs and value contributions of each step provides a means to measure the efficiency of its conversion processes. The more value contributed in a process step the more financially efficient is the step. By knowing the cost of all inputs and all wastes, you can identify the steps having the greatest effects on operating profit. With each step's contribution information, managers, accountants and engineers can focus on new cost reduction, productivity and process improvements that return the best value.

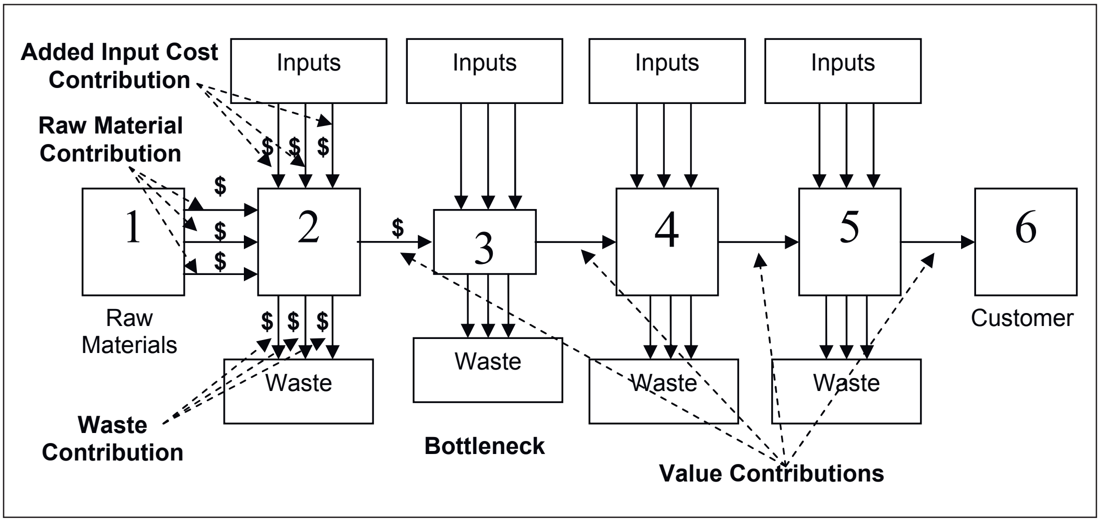

Figure 15.4 – Production Process Money Flows.

Figure 15.5 indicates how to identify each money flow associated with a process step. The boundary line makes it clear there is money entering from 'raw materials' and the added inputs required in making the process conversion. Each process step delivers its own process 'product' with its value contribution from the value-adding performed in the step. In addition, there are lost moneys that reflect process and operating inefficiencies, wastes and losses.

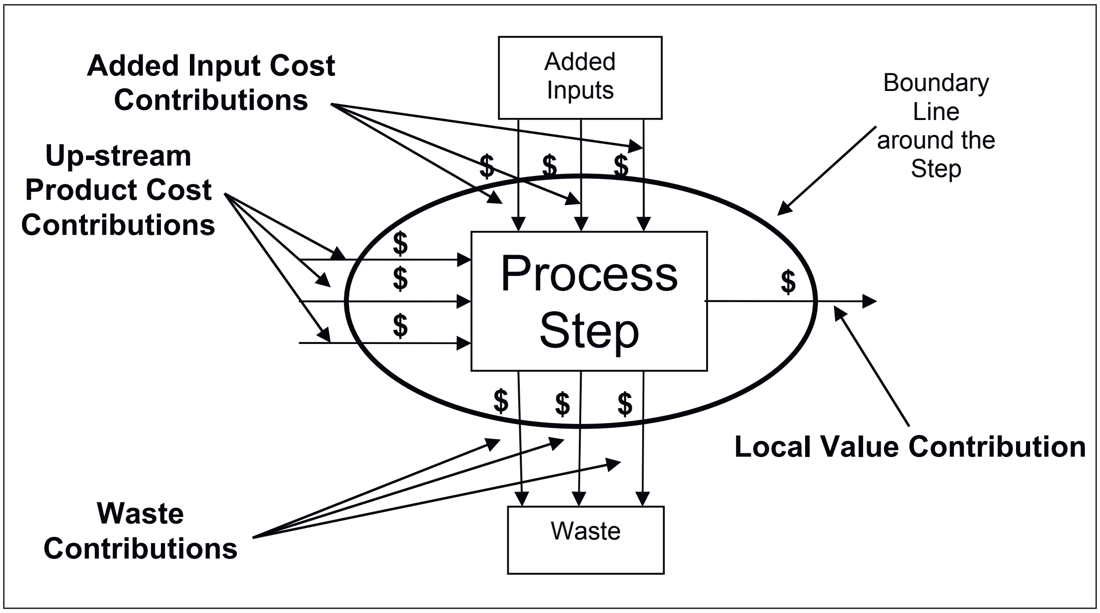

Figure 15.5 – Local Process Step Money Flows.

By identifying a business as a process of interconnected steps, it becomes possible to focus on the financial performance of each step and optimise it. Process Step Contribution Mapping manages operating performance hour by hour by monitoring the costs into and the value out of each process step. Once a step's in and out money flows are identified they are used to analyse its profitability. The necessary equation is:

Raw Material Cost + Added Inputs Cost = Value Contribution + Waste *Eq. 15.1*

The value contribution is found from equation:

Raw Material Cost + Added Inputs Cost – Waste = Value Contribution *Eq. 15.2*

Strangely, from equations 15.1 and 15.2, it seems we pay for waste twice, once when we buy it as an input and second when we throw it away as lost value.

The Process Step Contribution Map

To identify money flows it is best to start by drawing a cost map showing the money movements occurring in the entire process. A simple Process Step Contribution Map is shown in Figure 15.6 for a section of a beverage canning line. Costs cascade into a step and wastes from the step.

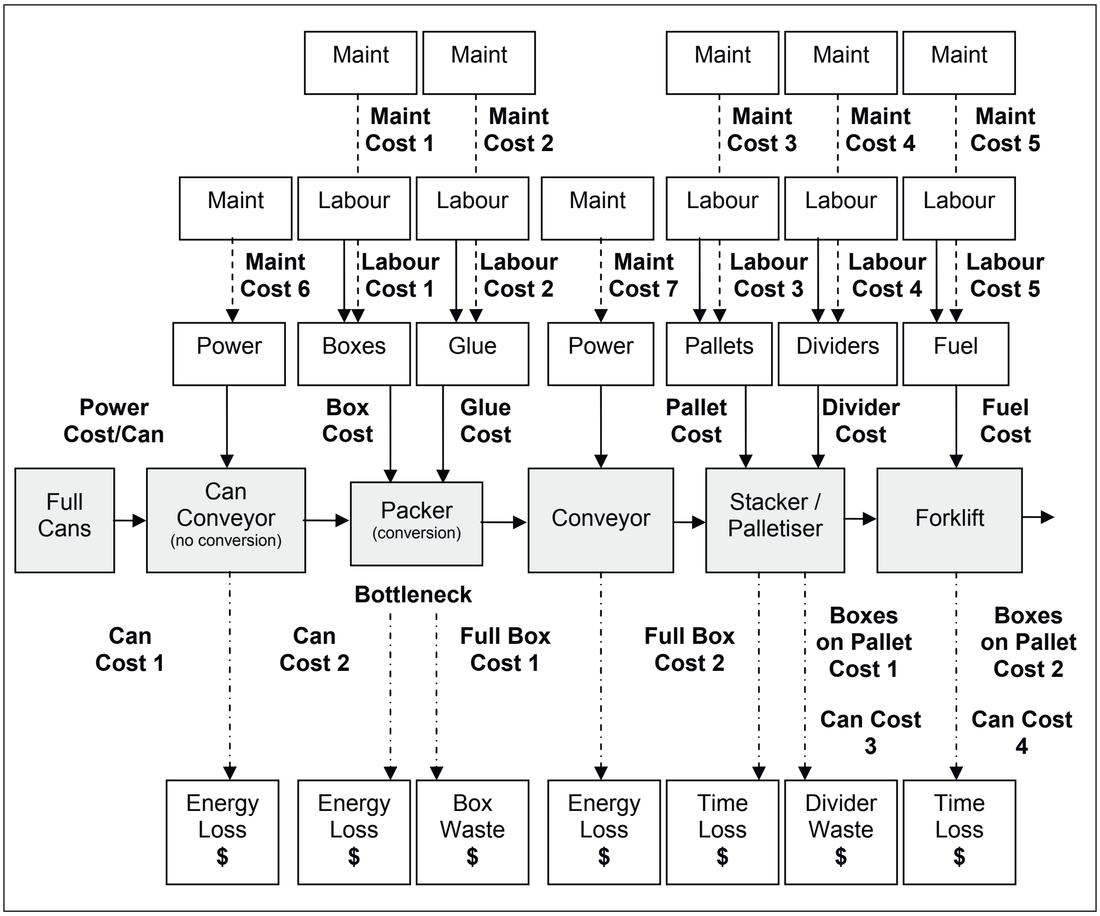

Figure 15.6 – Process Step Contribution Map for a Canning Line.

Cost Analysis

The power of Process Step Contribution Mapping is the clear financial understanding provided of the real value produced in each production step. By displaying where the money goes into, around and out of a process, the cause of costs and profits becomes clear to people.

It is important every dollar spent in the production of goods is accounted for on the process-step contribution map. It is necessary to capture every cost, from the smallest to the largest, as it is spent. Activity Based Costing (ABC) is the most appropriate accounting technique to apply when determining process step costs. Standard costing is not suitable since overheads are allocated as a proportion of total direct costs of a process and not by individual process step. It may be necessary to do time and motion studies in the workplace to identify all time and resources used in a step. ABC is used to identify every cost with its component costs, and even sub-component costs.

The reporting frequency for a process step depends on the step cycle time (how long it takes work to be processed through the step) and how long it takes to measure all money flows for the process step. The appropriate period used to measure the mapped costs should be as short as possible to give feedback quickly enough to match the volatility and importance of a situation. With the progress of computerisation, electronic tracking of material and automation of cost information, it is possible to give value contribution information to every operator in a business. Process Step Contribution Mapping lets shop floor people see how their process behaves so they can adjust their behaviours and decisions accordingly.

Real-time cost collection is ideal, but that requires using computerised on-line recording of all inputs, outputs and wastes, along with the software to processes the data and display it. Reporting during and at the end of a processing cycle is useful for adjusting process efficiency. In some cases, it might be necessary to map a particular process step more often than the entire process because of its importance in the operation. The process step contribution map ought to be updated for each shift so people can identify opportunities to improve every day. When Process Contribution Maps are generated weekly or monthly they become historical indicators for reviewing process effectiveness.

Developing Profit Contribution Equations

The money movements on the cost map represent the materials, labour, wastes and the value-added for each step. They can be represented by an equation of the type shown in Equations 15.1 and 15.2. The cost of producing product through the whole process is simply the amalgamation of the individual steps. A financial model with such engineering precision permits the monitoring of the real cost of production and allows determination of how profitable it is to do a job. It identifies where there are costs and wastes to remove to get the maximum operating profit. Because most businesses cannot measure their process wastes it often needs perseverance and creativity to gather the data and to develop the equations. Once a process and its steps are mathematical detailed it is a simple matter to conduct 'what-if' sensitivity analyse to identify the critical success factors affecting its optimisation. It then becomes clear where the process needs to be changed to maximise performance and profitability.

Where detailed monitoring of all process step money flows is not available, an approximating cost model is developed. The approximating equation is based on the costs related to a unit of production. Example E15.1 shows how Profit Contribution approximating equations are developed for the manufacture of concrete reinforcing steel in an operation that could not introduce process step money flow monitoring.

Collecting Cost Data

A production process generates the cost data needed for analysis and management as it makes the product. The cost of materials, labour, utilities, overheads and services are on invoices or payslips. Not normally available are the process costs accurately allocated to the process steps that incurred them. To manage a process step's efficiency it is necessary to cost every input, product and waste accurately. An approach used to identify the money flows in a process step is to use the process step job procedures and work through them identifying the process step raw materials and inputs added, the wastes produced and the product made. As shown in Figure 15.3, put a boundary around the step to clarify the associated 'flows'. Many of the inputs, wastes and products are on the process design drawings, or found in engineering documents, equipment manuals and standard operating procedures. Confirm the data by personally observing every step for a full cycle of production.

Onsite identify all electrical power supplies to the equipment, all pipes suppling services, all process products into the step, all added inputs, all outputs and wastes from the step. This includes measuring all manpower and overhead persons' (such as management, supervision, information technology specialists, etc) efforts, times and costs incurred by the process step. It incorporates measuring forklift movements, vehicle movements, personnel movements, etc. that occurs in the period observed. It includes counting the number of lights and time they are on, how often equipment is hosed-down and the amount of water used. Collate and cost all activities in a spreadsheet. It will be necessary to go as far as identifying minor costs, like rags used for cleaning equipment, the cleaning detergents used, any personal safety equipment and company brought clothing each operator requires during the period, etc. Over a year, these minor expenses can grow into serious costs that are easily wasted. Find every dollar that goes into a process step and that comes out of it. Put on the mantle of the crime investigator and look for all the clues to the puzzle. Unearth the truth of where the money goes in each step.

When studying a process step that involves movement of product and/or people, for example storing materials in a warehouse, time the length of the move, measure the distance moved and identify the equipment used in the work. Put a cost to the movement of product and materials to test if it delivers real value for the expenditure.

Because the Process Contribution Mapping process needs to identify every cost individually, it is preferred that all overheads be identified separately as they are used in each process step. By allocating overhead costs proportionate to direct labour, an inaccurate mapping of the true costs result because overheads are not really expended in proportion to labour hours. But if it is not possible to allocate overhead costs separately, they can be allocated in proportion to their identified usage in each process step. The accuracy and completeness with which the process step costs are collected will directly determine the effectiveness of the step contribution map as a management control tool. If data is complete and true, then it is believable and useful for decision making.

All costs are in business systems such as payroll, inventory and accounting. Unfortunately, they most likely will be totalised costs. The labour will be for a person's total time at work and you need what they spent in each process step. The power bill will likely be for the whole of a building, whereas you require the cost of lights and power for each machine in that building. The purchase of safety gloves will be in batches of dozens at a time but it is necessary to know how many the people working in a process step used.

The most accurate approach is to get the real usage of inputs and wastes. For example, the power used by the lights and machinery in the process steps need to be collected for the period concerned. If that is not possible it becomes necessary to proportion the machine's share of the building's power based on the electric wattage used in the process step. But by proportioning you introduce inaccuracies that may cause people to question the conclusions. If necessary, introduce special means to capture cost information. Develop timesheets and record-of-use sheets, connect chart recorders to electrical equipment and install Doppler-effect meters to measure flows in pipes. If accurate cost control is important to the success of a business then spare no effort to discover the true wastes, costs and losses you suffer.

Capturing Process Step Costs

The work involved in identifying and costing component inputs, products and wastes for each process step can be large. Use modern technology and computerisation as much as possible to capture as many of the costs automatically. Identify labour by using electronic time cards and time clocks. Electronic tagging or bar coding can be used to identify material movements. With Global Positioning Systems your equipment, materials and people movements are traceable.

If wastes cannot be identified electronically it becomes necessary to conduct site surveys to quantify them in order to develop a factor for use in calculations. It may be useful to change work procedures and include the recording of process step waste as standard practice. If waste is not regularly measured, conduct audits periodically to confirm the waste factor allowance and alter the Process Step Contribution Mapping equations as necessary.

Even if Profit Contribution Mapping is not adopted by your organisation, consider permanently introducing the counting and measuring of wastes to allow identification of the causes so you can address them before they get even worse.

Labour

Direct Labour comes from the time sheets of the people employed directly in the process step being analysed. If the people work in another process step, then only cost time expended in the process step under investigation. The direct labour cost is the pay rate, including on-costs, paid to the people working in the process step, multiplied by the time they spend in the process step during the period costed. Their on-costs include allowances, superannuation, benefits, etc, proportioned to the period. Do not include allowance for overheads, as they are separately costed.

Indirect labour costs are the time spent by persons, other than the directly involved people, to complete the process step. It is necessary to measure and allocate times for indirect labour. This includes maintenance, supervision, middle and senior management time, inventory and storage personnel, purchasing department personnel, quality control personnel, etc. Identify these costs by interviewing relevant people to find out the time spent on various process steps. During a site inspection watch the process for a full production cycle and observe who interacts with the process step.

The indirect labour cost is the pay rate paid to the indirect people, including their on-costs, multiplied by the time they spend in the process step during the selected period. On-costs include allowances, superannuation, benefits, etc, proportioned to the period. If indirect labour is missed over a short period, a proportion of all the missed indirect labour costs still need to be allocated to the period. Take a longer time and collect all the indirect labour costs for the longer period. Then proportion and allocate them for the period being reviewed.

Indirect expenses are those costs incurred due to the presence of the 'indirect' people in the operation. An example is a manager's car and fuel paid out of operating revenue. Allocate them in proportion to the hours spent in the process step by the expense owner.

Subcontractors

Allocate subcontract labour and materials the same as employed direct labour. There will be an invoice for the subcontractor's time and materials, and from it is extracted the allocation of times and materials for the work done in a process step.

Utility Services

Measure electricity, water, gases and such services and allocate to the process step usage during the period.

Management, Engineering, Administration, Supervisory Costs

These costs cover the time managers, engineers, supervisors and administrative support staff spend doing work related to requirements of the process step. For example daily meetings, site inspections, human resources requirements, problem solving process issues, invoice matching, stores management, maintenance planning, etc. All support persons who interact with the process step need their times and costs recorded against the step. People can be interviewed and asked to estimate the time they spent on a process step. If necessary have them keep time sheets to record the actual times involved with the process during the period.

Added Input Materials

Direct material costs are for added input materials actually used in the process step. They are the obvious additions of substances into the process step. This includes such things as electricity for motors, boxes for packaging, lubricant for equipment gearboxes, air for pneumatic rams, etc. Typically, these materials enter the process step in a physical form. These costs depend on the quantity and value of each input material used. It requires counting the amount of the material used and multiplying by the unit cost of the added material. Identify material costs from invoices for the material. Sometimes the added material is from within the organisation and no invoices are available. In such cases it will be necessary to get an accurate cost for the added material from the process used to make it. If none is available calculate it from the cost of the labour, ingredients, handling and manufacturing charges, etc, used to make it.

Indirect material costs are the costs associated with the indirect functions required to perform the process step. Such as paper for recordkeeping, electricity for office lighting, a maintenance planner's computer, the cost of forklift hire to move pallets, the building storage space for spare equipment parts, etc. All these costs are real costs incurred to conduct business that supports the production processes. It is necessary to measure them and quantify them so that they have a value. Measurement can be by stopwatch, distance, counters, etc. Identify the proportion used in the step and the amount wasted.

Raw Material/Up-stream Product Costs

Determine the cost of the raw materials and/or up-stream products entering a process step. An accurate value may be available from the accounting, or production department. If it is not available accurately it will need calculation for each prior process step from the start of the process.

Identifying and Costing Wastes

Direct waste is any direct labour or direct materials added into the process not fully used-up in making a product. Where an added input gradually converts through a number of process steps, it is not wasted if is is fully used. Unconverted added-input is waste. For example, in some chemical processes the chemical reaction absorbs only a portion of the mixed ingredients. Those ingredients not converted by the reaction are wasted. A laboratory analysis can identify unconverted ingredients and tell how much was unused. Another example is water used to clean equipment. It does not go into the product but disappears out of the process and is a waste. Leakage from the process is waste. Spillage from a process is waste even if it is pickedup and returned to the process. Another example of waste is side-steam materials collected in bags or bins and disposed of as rubbish.

Indirect wastes are those wastes related to the unnecessary use of indirect labour and indirect materials. They are more difficult to identify because they are not easily observable. Examples include wastes related to lost time in meetings, to lost energy, to lost compressed air, to safety equipment thrown away before fully used, and storing unneeded materials in a storeroom. There are numerous instances of such wastes. The detection of indirect wastes is through observation. Observe all process steps and their inputs to identify wasted costs, materials and product. Look in the rubbish bins used in the process step area and see what people throw out. Include the lights and air conditioning left on overnight unnecessarily. Develop and instigate systematic means to spot and record the waste and its value during the period investigated.

Comparison with Standard Costs

Every organisation should have a standard costing system for its products. If standard costs are available, use them as a parallel double-check and compare them with the costs from the process step mapping analysis. Investigate variations of more than 10% from the current standard costs because the variation shows that there is a pricing problem.

Performance Measures and Reporting

Problems highlighted by profit contribution analysis require Management and personnel to use new strategies to maximise the value from their processes. After a process step is analysed in detail it is easy to understand and appreciate how its many factors interact and impact each other. The accurate costing of inputs, wastes and conversions will identify efficiency problems. Through detailed questioning and root cause investigation, the reasons can be uncovered and then the required changes can be made. If change is required it is necessary to determine what that change will be. Issues will need discussion with everyone concerned in order to fully appreciate and understand their history. The new changes will also need discussion, review and analysis for possible unwanted consequences. New changes introduced will require their own measurement, monitoring and reporting.

Selecting the right measures to monitor and report will be critical to the success of the change process and to the speed of its implementation. The measures need to be meaningful to the users, truly reflect the situation, be within the user's control to improve, and inspire continued improvement. One of the change strategies will be to introduce performance measures that identify poor efficiencies and the practices that cause them.

Performance measures based on the issues identified by the analysis are intended to drive the right behaviours and actions. Use process control charts, graphs and trends of the measures to show performance improvement. Some typical indicators to use are listed below. Measures must suit specific circumstances. The purpose of measuring is to know exactly what is happening. After understanding the current situation an assessment is made as to whether it is satisfactory, or it needs to be changed. The effects of a change will appear in the performance measures. It may take as long as several weeks or months to observe the effects of a change. Where the measures indicate an unsatisfactory result a correction is necessary to get back on-track.

Usage Efficiency: This is the classic output divided by input. Select the important process flows. Develop appropriate efficiency measures for each, and trend them over time.

Productivity: These are measures of process performance. They are time based ratios of output during the period. From the contribution map select the productivities that are important to measure. Measure Productivity at both the process step level and the global process level.

Throughput: This measure is a count of what passes a selected point in the production process during a period.

Waste Cost: This measure counts the cost of waste in dollars per dollar spent to purchase the original material.

Quality: Is the proportion of production that meets customer specification. It is another measure of a wasteful process.

To get a complete understanding of what happens in a process requires more than one measure. Business processes involve many interactions and may have several variables that affect each other. It may take a number of ratios to identify what is occurring, though you do not want to use more measures than necessary. Maintaining measures requires time and money, which are then not available for use elsewhere. Experiment with the right measures to apply before deciding which to use. Keep performance reporting simple by using headings to categorise reports and visual means for displaying information. Show trends graphically in a form that makes their message clear. Use balloon notations in graphs to highlight issues that need attention. Apply colour and font variations to enliven the report. In tables show summary entries and totals for each category. Keep the details for when people ask. Draw people's attention to the conclusions and their implications by providing an executive summary at the start of the report.

Example E15.1: Process Cost Mapping

Approximating Cost Equation for a Manufacturing Process

The organisation produces bent and straight reinforcing steel bar used in building construction by uncoiling rolls of different size bar through a machine, which then bends the bar to the required shape and cuts it off the coil. The cost map for the production is in Figure 15.7. The cost map shows the manufacturing process with each machine. It breaks the manufacturing process into its separate steps to show where costs arise during production. The manufacturing process runs horizontally across the page and the costs incurred at each step run vertically into the process at the step. The cost map identifies every input cost and waste for each step. Realise that every input to a step is itself the result of another process, which the contribution method can also analyse.

By laying-out the process in a flow diagram it becomes clear which steps incur costs and from where costs arise. To have a cost equation that correctly represents the money flows we must have all input costs and all outputs for each step. If the actual costs incurred at each step are not available it is necessary to develop cost estimates from accurate historical data, or by observing the step and recording inputs, outputs and wastes.

Difficulty arises when there is no real data available for individual inputs and none can be collect on-site. In such cases it becomes necessary to allocate costs using standard cost methods and hope they closely reflect the real situation. Figure 15.8 is a simplified version of the cost map in Figure 15.7 where costs are allocated and proportioned for each individual step as advised by the operations management and accounting people in the business. This example describes a means to estimate the cost of producing a piece of work through the production process shown in Figure 15.8. The requirement is to represent the production process by a cost equation so that estimates of the cost of work can be made in order to determine if it is profitable to do a job and to identify where costs can be saved in producing the item. Each work piece from the cutting and bending machine consists of lengths of bar either made straight or made with bends and straight lengths between bends. The cost of a work piece depends on its diameter, the length of material used, the number of operations and movements performed on it at each step, plus its share of unmeasurable business costs allocated to each step.

The variables for the steel bar production are:

- Bar diameter
- Work piece total length
- Number of bends in a work piece
- The bend complexity
- The total factory production time for the work piece

Once the cost to produce one unit of work is know, then the cost per production run can be estimated by multiplying the cost of a production unit by the number of units to be produced.

Taking each process step one-by-one from the start of the process, the cost map allows easy identification of component costs and wastes. Reflect each step in the form of calculation shown by Equation 15.2, and repeated below.

Raw Material Cost + Added Inputs Cost – Waste = Value Contribution

Applying the equation to the 'Received in Factory' step from Figure 15.8, its value contribution equation is:

Cost of steel coil to make a unit of product + That step's proportion of allocations for one unit of product = Step value contribution per unit processed

For the 'MACHINE – Coil / Uncoil / Straighten / Bend / Cut' step its value equation is:

Value carried from prior step + Labour for the step to make one unit of product + Power used in the step to make one unit of product + Maintenance on the machine caused by one unit of product + That step's proportion of allocations for one unit of product – Scrap from one unit of product = Step value contribution per unit processed

Perform this calculation for each step in the process with a computerised spreadsheet. The analysis identifies the value-added at each step, and the impact of its costs and wastes. If the unit of product is too small to get sensible unit costs then use the smallest multiple of units for which costs and allocations can be reliably and accurately determined.

Model the entire production line or process by adding together the equations for each process step.

Developing the Cost Equations

The first step is to draw the complete process as a flow diagram showing each stage of production as a separate box on the flow diagram. Within each box briefly name the step with words that describe its function so it can be identified separately to other steps. On the flow diagram identify every input, output and waste for each step.

It is necessary to identify and separate the fixed costs and the variable costs for each step. Typically, fixed costs are a constant cost for the business and do not change with the work, whereas variable costs are dependent on the work piece and change as the type of work changes. The production cost consists of the fixed costs and variable costs added together. The basic form of the production cost equation is:

Production Cost = Fixed Costs + Variable Costs

To be able to use the equation for every item of work put through the process it is best to base the costs incurred in production on factors related to the work piece itself. Allocate costs related to variables that change with the type of work piece so that the estimated cost reflects work piece complexity. For example diameter, size, weight, complexity, etc. These variables in the case of the steel bars are:

- Bar diameter (available from the design drawings).
- Work piece total length (available from the design drawings).
- Number of bends in a work piece (available from the design drawings).
- The bend complexity (available from the design drawings).
- The total factory production time for the work piece (available from standard costs or a work and motion study is performed to determine typical production times).

For each process step in the cost map write the costs associated with its inputs and wastes. Separately describe the logic behind developing the cost equation so that there is a reference explaining the equations (see the descriptions at the end of the example).

Keep variable costs and fixed costs separate. The variable costs connect to factors related to the work piece, whereas the fixed costs are independent of the work piece. Collect costs into a summation equation of identical variables. Look for means to arrange and combine costs and simplify the equation where possible. In this way, work through each process step to develop its own equation. The total process is the sum of its individual steps.

The example cost equation below combines the individual process steps into an overall equation for the steel bar production process. The numbers in *italics* reference the description of the costs.

The cost for each work piece depending on its diameter consists of:

Variable Cost / metre straight = Cost of machine power to feed and straighten coil *(2)*
+ Handling/bundling labour, including on-costs *(3)*
+ Maintenance of coil holder, rollers, etc due to machine use *(4)*
+ Steel cost per metre (12mm and 16mm) *(1)*
+ Coil loading – crane and labour, including on-costs *(8)*
+ Straightening rollers set-up labour, including on-costs *(11)*
+ Scrap, including crane movements of bin *(13)*
+ Finished tag storage – building amortisation & maintenance *(17)*

Variable Cost / bend = Steel cost per bend (12mm and 16mm) *(5)*
+ Cost of machine power to do a bend *(6)*
+ Maintenance of machine due to use *(7)*
+ Bends' set-up labour, including on-costs *(12)*

Variable Cost / work piece = Scheduling, including on-costs *(9)*
+ Finished job moving – crane & labour, including on-costs *(14)*
+ Loading truck/trailer – crane & labour, including on-costs *(15)*
+ Despatch to customer – paperwork, invoicing *(16)*

Fixed Costs / production hr = Supervision – Leading Hand, Supervisor, including on-cost *(19)*

+ Invoice processing, including on-costs *(18)*
+ Production Planner, including on-costs *(20)*
+ Senior Management/Accounting costs and on-costs *(21)*
+ Hire of factory crane *(22)*
+ Maintenance – crane *(23)*
+ Maintenance – general costs and building *(24)*
+ Factory lighting *(25)*
+ Offices' running costs (Admin Office, Production, Despatch) *(26)*
+ Safety *(27)*
+ Quality Control *(28)*
+ Estimating and quoting, including on-costs *(10)*
+ Customer disputes and resolution, including on-costs *(29)*
+ Production Coordinator *(30)*

The cost equation for the complete process for a unit work piece becomes:

Production Cost = Cost per m straight

+ Cost per bend

+ Cost per piece

+ Cost per production hr

Once the cost of one work piece is know, then the cost per job size can be estimated by multiplying the cost of a work piece by the number of work pieces required.

Derivation of Process Step Costs

(1) Steel cost per metre (12mm and 16mm)

This is the cost of one metre of coil delivered into store. It includes:

- all steel mill cost
- all transport costs nationally and locally
- all off-loading forklift use and labour
- delivery documentation processing
- all stores receiving and inventory updating
- the cost of storing the coil on-site, such as rates, land tax, site maintenance, etc.

Both 12mm and 16mm coils go through the machine. The cost is required by metre length.

(2) Cost of machine power to feed and straighten coil

This is the power required to unroll the coil and run it through the straightening rollers. It will vary for each size of bar. The cost is by metre length.

(3) Handling/bundling labour including on-costs

This is the labour cost to wait and grab a work piece, then lift, move to the stack and place it onto its bundle, including the time needed to tie the bundle for a lift to be despatched. The time taken depends on the size (length x width) of the work piece. The cost is by metre length.

(4) Maintenance of coil holder, rollers, etc due to machine use

This cost is from the wear and tear on running parts used to unroll the coil and run it through the straightening rollers. It can be estimated by metre length from the cost of replacement parts (coil holder and straightening rollers) plus the labour to change the parts divided by the total length of coils put though the machine in the time since replacing the last set of roller parts.

(5) Steel cost per bend (12mm and 16mm)

The cost of steel required for a bend. Both 12mm and 16mm bends go on the machine. For a 90^{o} bend this is three-quarter the bar diameter. For an 180^{o} bend it is one-and-a-half times the diameter.

(6) Cost of machine power to do a bend

This is the power required to put a bend in the steel. It will vary for each size of bar and amount of bend. The power is best determined by using a power meter mounted on the machine to measure the power used over a long period of time (at least a week). Alternately, make a rough estimate from the electric motor size and the length of time it is used.

(7) Maintenance of bender due to machine use

This is the maintenance cost of the bending head on the machine per bend. Calculate it by the maintenance costs over a period divided by the number of bends performed by the bender during that time. The number of bends in a period comes from historical records or by site observation.

(8) Coil loading – crane & labour, including on-costs

This is the cost to forklift the coil into the building, lift it by crane to its uncoiling cradle at the machine and return the crane. Labour cost is also included. Because a coil is of known length, calculate this cost by the metre.

(9) Scheduling, including on-costs

This is the cost to schedule a work piece. It includes the time spent reviewing the drawings, calculating measurements, entering information into the business systems and printing and handling paperwork, including the cost of stationery. From the scheduling process the bar schedules are developed. A cost per work piece can be determined from the cost of time spent per schedule, divided by the number of work pieces in a schedule.

(10) Estimating and quoting, including on-costs

This is an hourly cost allocation for the time and resources taken to estimate and quote a job, multiplied by the time taken to make a work piece. The bigger the job the longer the time taken to do these tasks. The cost can be determined from historical averages of time and resources required provide prices to customers.

(11) Straightening rollers set-up labour, including on-costs

This is the time required to adjust and set the machine to straighten bar and test its performance. Calculate the cost per metre length by dividing the time taken to set-up with the length of the coil. It assumes that there is one set-up per coil, which is less than actual, as a bar size change can be required a couple of times a day.

(12) Bends' set-up labour, including on-costs

This is the cost to set-up the machine to do all bends required in a schedule divided by the number of work pieces for the schedule and again divided by the number of bends in a work piece. All work pieces in a schedule are identical. Calculate an estimate from workplace time and motion study for several different work pieces and persons and averaging the time per bend. The more complicated shapes involving non-90^{o} bends will require a 'complexity factor' to allow for the longer time these take compared to a standard 90^{o} bend. The suggested complexity factor is one (1) for 90^{o} bends and two (2) for all other bends.

(13) Scrap, including crane movements of bin

This is the cost of scrap, which runs at 2% of steel bar throughput, or 20mm per 1000mm. Two crane movements, removing scrap and replacing the bin, are also required in the cost. A more accurate scrap rate allowance for each machine is by weighing the actual scrap generated by each machine monthly for a number of months.

(14) Finished tag moving – crane & labour, including on-costs

This cost is for moving each finished tag by crane from the machine to its storage space on the floor divided by the number of work pieces in the tag. Allow one crane lift per tag.

(15) Loading truck/trailer – crane & labour, including on-costs

This cost is for moving each finished job by crane from its storage space on the floor to the transport vehicle divided by the number of work pieces in the job. Allow one crane lift per job.

(16) Despatch to customer – paperwork, invoicing

This cost covers the time spent on each tag by the people in Despatch handling paperwork and inputting into business systems divided by the number of work pieces in the tag. Collect the cost by counting the number of jobs processed in a period by the Despatch personnel and dividing them by the total number of work pieces in the job.

(17) Finished tag storage – building amortisation & maintenance

This cost is that required for the floor space within the building including rates, land tax, building maintenance, etc. The floor space relates to the length of the work piece. Estimate the cost per metre length by conducting site surveys of the typical foot print of a range of work piece types and dividing the cost of each type by the total length of the steel in the work piece.

(18) Invoice processing, including on-costs

This cost covers the function of creating and processing customer invoices, including rectifying invoice problems. Estimate the cost from historical averages of processing time and allocate per production hour for a work piece. Multiply hourly cost by the estimated hours to produce a work piece. The time for work piece fabrication comes from historical records or by site observation.

(19) Supervision – Leading Hand & Supervisor, including on-costs

This is the hourly cost for the leading hand and supervisor multiplied by the estimated time a work piece will take to produce.

(20) Production Planner, including on-costs

This is the hourly cost for the Production Planner, multiplied by the estimated hours a work piece will take to produce.

(21) Senior Management/Accounting costs and on-costs

This is the hourly cost for senior office staff, multiplied by estimated hours to produce a work piece.

(22) Hire of factory crane

This covers the hourly hire for the cranes in the steel bay allocated by machine, multiplied by the estimated hours a work piece will take to produce on the machine.

(23) Maintenance – crane

The cost of crane maintenance per hour multiplied by the estimated hours to produce a work piece.

(24) Maintenance – general costs and building

This is the cost for non-specific machine maintenance in the steel bay, and associated building, allocated to each machine, multiplied by the estimated hours to produce a work piece.

(25) Factory lighting

This is the hourly cost for lighting in the production area, multiplied by the estimated hours to produce a work piece.

(26) Offices' running costs (Front Office, Production, and Despatch)

The hourly cost to run the Administration, Despatch and Production Offices and equipment (power, water, air conditioning, cleaning, stationery, etc); multiplied by the estimated hours to produce a work piece.

(27) Safety

This is the hourly cost of safety personnel, safety systems, personal protective equipment, etc, multiplied by the estimated hours a work piece will take to produce.

(28) Quality Control

This is the hourly cost of quality personnel, systems, documentation, etc, multiplied by the estimated hours a work piece will take to produce.

(29) Disputes and resolution, including on-costs

This is an hourly cost allocation for the time and resources taken to resolve disputes on a job. A cost can be estimated using historical data.

(30) Production Coordinator

This is the hourly cost for the Production Coordinator, multiplied by the estimated hours a work piece will take to produce.

Calculating Crane Lift Cost

The cranes move job bundles about the production floor and unload/load transport vehicles. Each lift requires the hoisting motor and each movement requires the drive motor. To calculate the cost of a lift it is necessary to determine the power used by the motors while lifting the load and moving it from start to finish.

The weight of the load is variable and can be up to 5 tonnes. However, normal practice is to load transport vehicles in 1-tonne loads for ease of site off-loading. To simplify and standardise the situation for each machine in the production line, a typical weight for each lift will be determined from site observation. The electrical power for a typical lift can be measured by an electrician. Use the cost of power for a lift in the production cost calculation for the relevant steps.

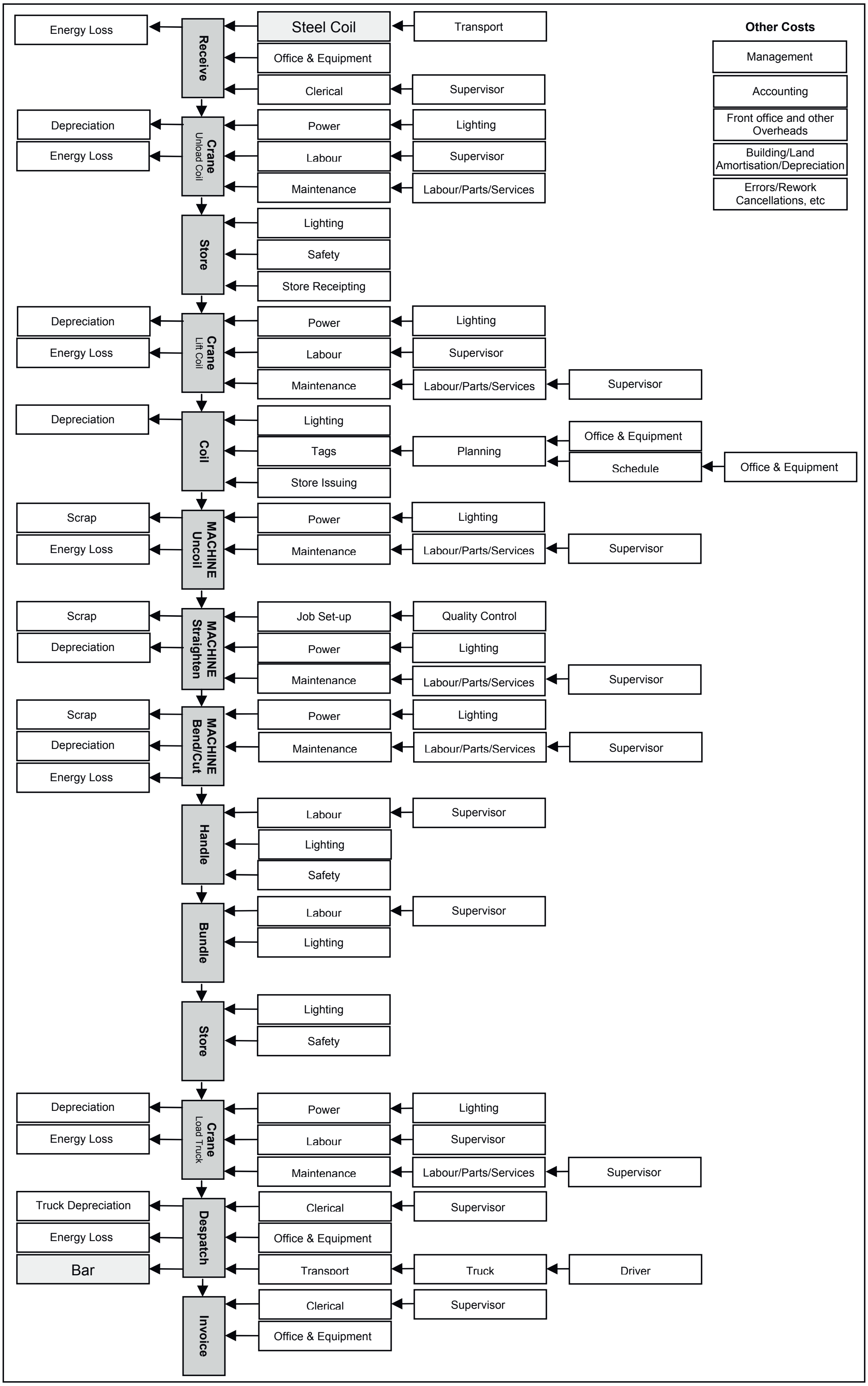

Figure 15.7 – Process Cost and Waste Map for a Production Process.

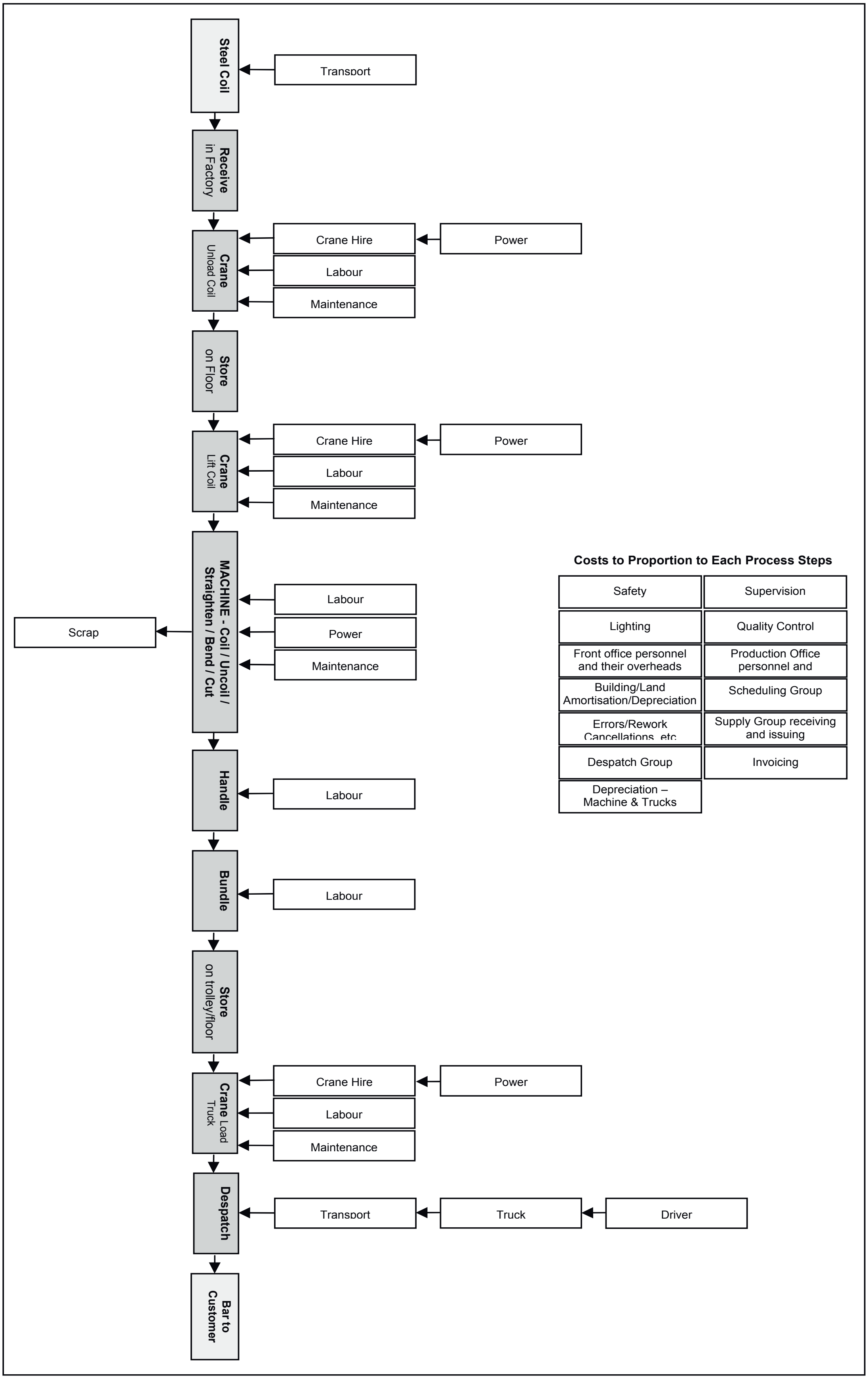

Figure 15.8 – Process Cost Map for a Production Process using Allocations.

16. Key Performance Indicators

Purpose of Key Performance Indicators

There is a story about a great industrialist that wonderfully explains the purpose of key performance indicators. A national magazine interviewed him for an article after years of building his business. The business was performing at world class levels and had been delivering average annual returns of 23% for the last eight years. It was a truly outstanding financial result. The journalist asked the industrialist how he had maintained such a powerful business performance for so long. The industrialist explained his methods.

During the years, as the business grew through both acquisitions and organic growth, he added operations and businesses to the portfolio. In time the business became a major multinational company with significant presence in the market. Clearly, he could not be everywhere at once to guide the many business managers now needed. It was necessary to develop a system to keep him in control while providing direction to the organisation and its thousands of people. Through continuously testing business performance measures, he settled on eight Key Performance Indicators (KPIs) suitable for the organisation, which he tracked each hour on his computer screen. These eight KPIs allowed him to run the entire conglomerate. He would know within half a day if there were problems in any of his businesses by reading the KPI graphs on his screen. If the trends were not right he would follow-up the problem with his managers until it was favourably resolved. Such is the power of Key Performance Indicators. They can proactively identify problems, provide direction and focus, measure performance and identify the necessary corrective actions.

When to Use Key Performance Indicators

KPIs reflect the efficiency and effectiveness of the conversion process from inputs to desired outputs. Use a KPI to monitor and trend the outcome of a process. Use KPIs to monitor change. Use them to measure the effectiveness with which a strategy is being implemented. When you want to measure effects in, or of, a process, be it a business, industrial or some other type of process, it is appropriate to track it with a key performance indicator. You compare the actual process performance against its ideal performance, or required performance. This permits identification of a discrepancy between what is wanted and what is actually happening. Once recognised, you can investigate both poor and good performances and make changes as necessary. A positive discrepancy can be analysed to learn what factors caused the good result and decide whether to make them standard practice. There is no limit on the range, scale, timing and use of KPIs. They can measure the performance of a single step in a process, right through to evaluating the complete process itself.

Why Use Key Performance Indicators

A KPI can offer many perspectives on an event. It can permit intense focus and scrutiny, detect changed conditions, score performance, indicate a change from plan, identify potential problems and it can drive improvement. When a KPI monitors and trends a process, the resulting figure tells you something about the process performance and its effectiveness. The KPI should be an accurate, honest reflection of the process efficacy in delivering the outcome. With a reliable KPI measure of performance the effect of a change or a new strategy reflects in the KPI results produced. The KPI will echo if the change improved the result, did nothing, or made it worse. Once you can monitor the effects of a change reliably, repeatedly and accurately by KPIs, they become tools to improve ongoing performance. Simply introduce the test change into the process and monitor its effect with the KPI. Keep those changes that work and discard those that do not produce useful results. Table 16.1 lists the range of uses for Key Performance Indicators.

Table 16.1 – Uses for Key Performance Indicators.

KPI Purpose	Description	Comments
Focus	monitor the results of actions	When it is not certain that a result is due to a specific set of plans and actions it is useful to introduce KPIs to detect and track what is happening. KPI measures that are thought to be appropriate can be trended over a period of time, and in different situations, to see if they in-fact highlight the relevant factors that are truly important to the successful outcomes from the actions.
Change	track the effect of making a change	If making a change to a process, how is one to know it will be a useful change? This is when an appropriate KPI, or a series of KPIs, will prove or disprove that a change is beneficial. If in fact the change makes matters worse the KPIs will prove it. Change things back to what they were or introduce and test make further changes.
Score	act as a means to measure progress toward achievement	Often the organisation's aim is simply to gradually improve what they do. In such cases the current performance becomes the base line for improvement and all future performances aim at being better than the last result.
Track	when you must meet set targets	When a target is set, it becomes critical to track the efforts used to meet the target. Put suitable KPIs into place to monitor the effects of the organisation's processes on meeting the targets.
Predict	proactively warn of future performance	In every organisation, there are people who are aware of the 'danger signs' that forewarn of future problems. Turn these indicators into KPIs that purposefully track and monitor, to prevent and reduce the risk of future failures.
Improve	drive continuous improvement	Where organisations have several similar operations, it is valuable to introduce identical KPIs into each workplace. This allows comparisons between groups. One group will always outperform the rest. With that group identified, investigate why it outperforms and introduce its methods into the other operations. In this way, the KPI system continually improves the organisation as a whole.

Which Key Performance Indicators

A KPI is often a mathematical ratio of one number over another, though it does not need to be. A single numerical count, or the recording of a completed number of actions, is suitable for many situations. When written as a ratio the KPI compares the current result against a previous result or a set target. The previous result or the target is the denominator that goes on the bottom line of the ratio. The current result is the numerator and goes on the top line of the ratio. Below is the typical way to calculate a ratio-type KPI.

$$\text{KPI ratio} = \frac{\text{Current result}}{\text{Previous result (or set target)}}$$

Or to identify the size of a change between past and present the KPI is written as:

$$\text{KPI ratio} = \frac{\text{Current result} - \text{Previous result (or set target)}}{\text{Previous result (or set target)}}$$

The choice of a KPI is dependent on the perspective you want to investigate. The industrialist mentioned at the beginning of the chapter was concerned to detect changes early so that he could make corrections before poor performance impacted on business returns. The KPIs were a proactive warning device. He would have selected data generated very early in the business process that reflected complications and losses arising later in his business. It is equally valid to use KPIs to reflect the issues that caused a problem. In that case the KPI is used to fault-find and highlight trouble spots to address and remove from the process. By removing problems the process efficiency is improved.

How to Develop Key Performance Indicators

The perspective taken when developing a KPI dictates the KPIs use. Its purpose affects the formula and the constituents chosen, when to measure them in the process, and how to use them to control performance. KPIs need to be relevant and meaningful to the performance monitored. Do not try and draw 'a long bow' to infer conclusions not directly supported by the KPI results. It is better to find a more appropriate, believable KPI, or introduce additional KPIs with the purpose of identifying and clarifying an uncertain situation, than to guess a conclusion.

Selecting the right Key Performance Indicator is critical to managing the desired performance. The KPI(s) must track the outcome(s) required. Equally important is to select the right factors, parameters or variables for collection and monitoring. For example, if on time delivery to customers is important, a suitable KPI would be to measure 'Required Delivery Date' verse 'Actual Delivery Date'. It would be less useful to track 'Planned Despatch Date' verses 'Actual Despatch Date' since a product shipped when planned could go astray during transport. It could get to the client late. Yet the KPI based on Despatch Date would appear acceptable, even if it were an unsatisfactory result for the customer. However, if you were tracking the performance of the delivery contractor, then it would be appropriate to use both the Despatch KPI and the Delivery KPI. You could track the reliability of their service in picking up the item on time and in delivering the item on time. If they do not meet a satisfactory target you have proof of their poor performance and can rightfully address the quality of their service with them.

There are five common methods used in selecting suitable KPI's measures and their constituents. These are the 'Input vs. Output' method, the 'Process Boundary' method, the 'Results Focus' method, the 'Best-in-Class' method and the 'Predict the Future' method.

Input vs. Output Method

For direct conversion processes that change an item from one form to another it is common to measure input quantities into the process and the quantities produced from the process. The difference reflects the efficiency and effectiveness of the conversion. For example, a KPI on electrical energy efficiency of a building air conditioning system would measure electrical power into the system against the cooling capacity of the system. Such a measure tells you how well the electricity you are paying for is converted. With this KPI you can trend day by day performance of the air conditioning system. A diagrammatic example of the 'input vs. output' approach is Figure 16.1. In the diagram, multiple materials enter the process and multiple outputs leave. You could develop KPIs tracking each input material's conversion, or an overall KPI tracking the total process. An example KPI might be – Proportion of Raw Material 1 used to make Product 3.

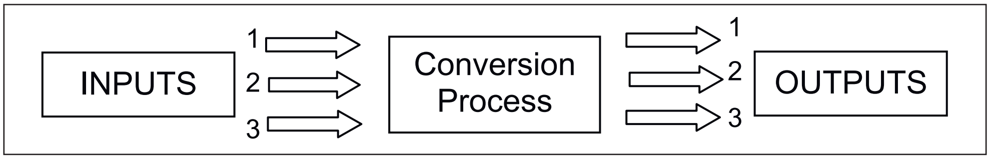

Figure 16.1 – Multiple Inputs Converted To Multiple Outputs.

In Figure 16.2, multiple inputs convert to a single output. In this case multiple 'input vs. output' KPI's can measure the effectiveness of individual conversions in the process.

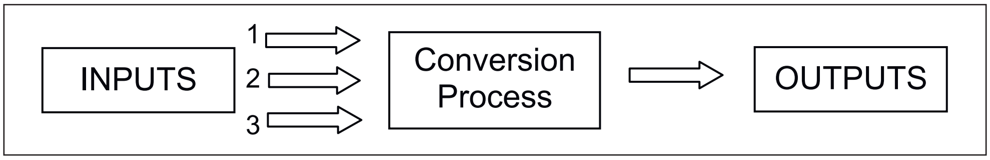

Figure 16.2 – Multiple Inputs Converted To a Single Output.

A secondary benefit from an 'input vs. output' KPI is to provide you with a benchmark to rate all other equivalent systems. Once you know what your current system performance is you can investigate other methods to see if they are better than the one you have. The other methods maybe within your organisation or maybe they are your competitors. When you find a better performing process you can recognise it and look for what made the difference between your methods and the other. The 'input vs. output' approach drives improvement to use existing resources better. Once you can measure the efficiency of a conversion reliably and accurately you have a 'tool' to test changes to further improve the process.

Process Boundary Method

Business or industrial processes can be represented on paper as a series of progressive steps linked one to the other in a process flow diagram. An example is a process logic flowchart for a manufacturing plant, or a flow chart for the processing of accident insurance claims in an insurance company. With the process flow shown on paper, a boundary is draw around the steps to monitor.

Many organisations already have their processes laid-out step-fashion in their quality system documentation. Most manufacturers have their processes laid-out in drawings. It is a simple matter to get copies of those documents and draw the KPI boundaries around what you want to measure. If there are no formal diagrams of the process flows you need to create them. It requires the people who know the various parts of the process well to sit down with pen and paper and flow chart the process. As the process develops on paper include the various inputs and outputs from each step. Once completed the flow diagrams are drawn and become official company quality documents to be controlled and up-dated.

Select KPIs that reflect what materials, documents or other inputs cross into the boundary region verses the materials, documents or outputs that come out of the boundary region. The process boundary approach typically results in multiple KPIs. The majority of businesses, organisational and industrial processes require monitoring several key factors at the same time. It is unlikely that one KPI alone will be sufficiently sound and robust to reflect all the factors affecting a process. Figures 16.3, 16.4 and 16.5 show how the process boundary method applies in a variety of situations. Draw the boundary to measure an entire process or the individual steps within a process.

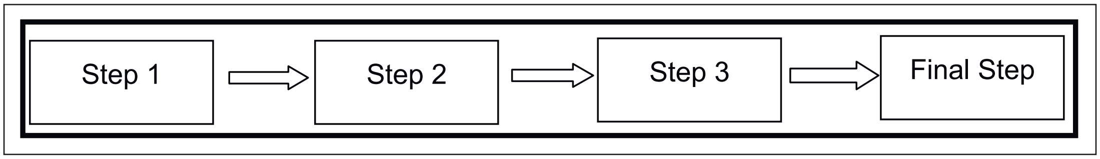

Figure 16.3 – Process Boundary Applied Across an Entire Operation.

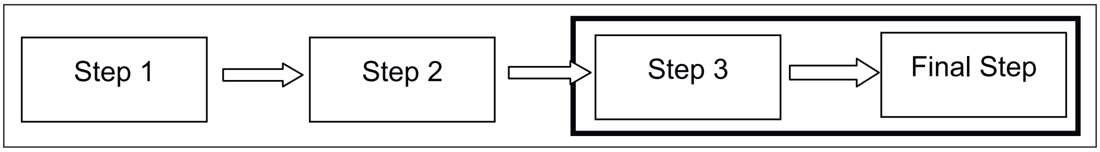

Figure 16.4 – Process Boundary Applied Across Part of an Operation.

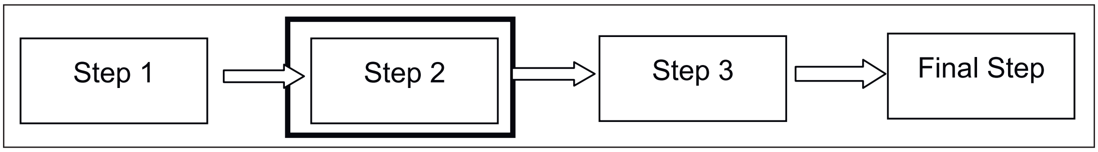

Figure 16.5 – Process Boundary Applied Across a Step in an Operation.

The Process Boundary Method is ideal for comparing process changes, or procedural changes, to evaluate their effect against another similar process. Figure 16.6 shows two processes compared by using the same KPI. One process would typically be the 'control' and the other process would be the test case which is changed. Once the boundaries are drawn, the various inputs and outputs for use in the KPIs are, by default, set and you will use them.

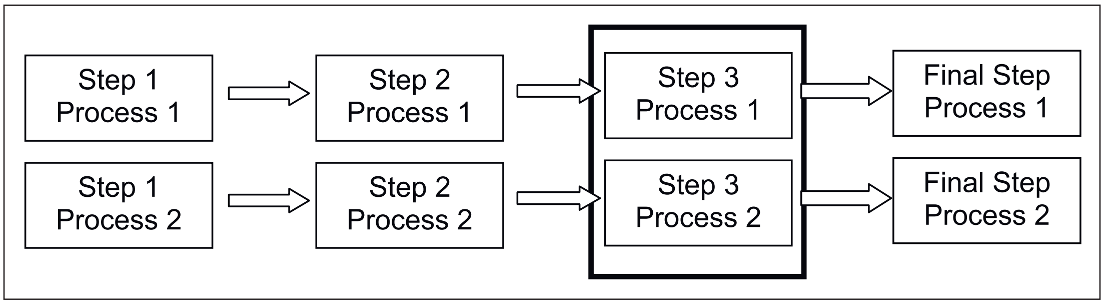

Figure 16.6 – Using Process Boundary Method Used to Compare Across Processes.

Multiple KPIs can be combined into one 'global' KPI that more simply represents the entire group's performance. An example of a 'global' KPI often used to measure manufacturing equipment performance is 'Overall Equipment Effectiveness' (OEE). OEE combines KPIs that measure production quality, production throughput and time available for production. The one measure blends the effects of the three individual factors into one number that reflects how the entire operation performed. The full KPI for OEE is below as an example of a single number that reflects multiple factors in an operation or process.

OEE = Availability x Performance Rate x Quality Rate

Availability – Percent of scheduled production (a measure of reliability) or calendar hours 24/7/365 (a measure of equipment utilisation), that equipment is available for production.

$$\text{Availability} = \frac{\text{Hours equipment was available to be used in the time period}}{\text{Total hours for period}}$$

Measures the equipment uptime (actual time that it was in production, or was ready for production) divided by the time that the equipment could be used (usually total shift hours) as a percent. (Equipment utilisation is different. It is actual production time divided by total calendar time.) Along with determining this KPI, it would also be necessary to record the causes of the losses and their frequency. Each of the causes can then be analysed and plans put into place to eliminate them.

Performance Rate – Percent of parts produced per time frame of the maximum Original Equipment Manufacturer (OEM) rated production rate. If the OEM specification is not available use the best known production rate over three consecutive runs.

$$\text{Performance Rate} = \frac{\text{Actual production output in the time period}}{\text{OEM rated production output for period}}$$

This measures the percentage of available time that the equipment is producing product at its theoretical speed for each individual product. It measures speed losses regardless of cause (E.g. inefficient batching, machine jams). Along with determining this KPI, it would also be necessary to record the causes of the losses and their frequency. Those causes can then be analysed and plans put into place to eliminate them.

Quality Rate – Percent of in-specification parts out of total parts produced per the time frame.

$$\text{Quality Rate} = \frac{\text{Number of parts in specification for the time period}}{\text{Total number of parts produced in period}}$$

This measures the percent of the total output that is good. Along with determining this KPI, it would also be necessary to record the causes of the waste and the frequency. Each of the causes can then be analysed and plans put into place to eliminate them It is necessary to address all product quality losses, including those due to production, handling, engineering design, etc that produced rework and scrap, otherwise no improvements will be permanent.

OEE Example: Availability (0.7) x Performance Rate (0.8) x Quality Rate (0.9) = 50% (which is a terrible result when compared to the world-class manufacturing benchmark of 90%)

KPIs like Overall Equipment Effectiveness become a benchmark target that:

- focus on improving the performance of machinery, plant and equipment already owned.
- find the areas for greatest improvement to provide the greatest return on investment.
- show how improvements in the process, such as changeovers, quality, machine reliability improvements, working through breaks, etc, will affect productivity.

Results Focus Method

This method requires that a target be set which becomes the goal for the individual, workgroup, department or organisation to hit. The target is the required result. When a specified performance output is set it becomes the only acceptable benchmark. It measures if the results meet the minimum requirements. The late quality guru, W. Edwards Deming, would abhor this KPI – it directly contravenes the spirit of his 14 Points of Management by placing quotas on people. But this KPI can be made to comply with his requirement if it is used to improve the process and methods and not to measure people's productivity. In that case the focus is on achieving a set target by intentionally forcing change to happen. The method is also known as 'push the limit', and can lead to world-class break-throughs.

The results focused approach flavoured with Deming's insight is very powerful, as it sends a clear signal that all past practices are open for review if changing them will lead to achieving the result. Often sales departments use it when quotas are set for product sales. Operating departments use it when production targets or quality targets are set. The target becomes the least acceptable result and the KPI tracks ongoing performance. Implicit in the results focused approach is the need to question the current process used to hit the target. If a target is not being met using the current process and systems, then changes are required that will produce the intended results. The results focused approach can create harsh and stressful work environments if managed badly. Yet if managed well it can introduce inspiration and adventure into the workday.

Best in Class Method

This approach for determining KPIs is relatively simple. You find those KPIs and performance targets used by the best organisations in the industry and adopt them for yourself. The one difficulty may be establishing systems within your operation to provide the data needed to measure the KPIs. Typically, 'best in class' organisations have already gone through significant changes which your operation has not yet been through. You may not have the same systems as they have and so cannot provide identical information for equivalency of comparison. This will necessitate introducing changes to your existing data collection processes so that the information is in a form that lets you truly compare your business against the best in your industry. The 'best in class' KPIs provide encouragement to employees and managers since they already have an example of a successful operation using them. All that they are required to do is try and catch-up with the best by developing a better operation. This makes introducing changes clearly justifiable and much easier.

Predict the Future Method

You can choose KPIs that predict your business future. These indicators measure the efforts put into improvement initiatives. For example, improving equipment reliability will increase production as downtime falls. But to increase reliability you must increase the technical skills and knowledge of the people running and maintaining the equipment. Increasing the amount of employee technical training, and improving its content, will produce employees capable of improving the reliability of their equipment. By using a KPI that measures the amount of technical and maintenance training these employees get, you would be gauging how well the plant will improve in future. Measure improvement effort with one KPI and have a second KPI to measure actual performance change.

Figure 15.7 – Measure Improvement Effort to Gauge the Direction of Future Outputs.

Good KPIs – Bad KPIs

A good KPI is believable and reflects the true situation in all circumstances. A bad KPI is one that can give you a false impression. For example, a KPI that measures actual results against planned results is rife for manipulation and presenting falsehoods. An example of a 'bad' KPI is below.

$$\text{Percentage Planned Production Completed} = \frac{\text{Production Completed in the Period}}{\text{Total Production Planned in the Period}} \quad (\text{x } 100)$$

It is easy to get great results with this KPI. Just do not plan to do a lot of work in the period. You can guarantee results close to 100%. People will manipulate this KPI to make management happy. Try and select KPIs that will only deliver the facts and the truth. If you use 'bad' KPIs that are manipulable, include additional KPIs that prove their veracity and robustness to see the whole 'picture' of the situation. With the 'bad' Percentage of Planned Production Completed KPI example above, it is necessary to have a second KPI that also measures the production load to check that the planned production does in fact load the facility fully to 'name-plate' capacity. With both measures presented together, it would then clearly indicate how well the production equipment was actually being utilised, as well as how well the operation ran.

Gathering and Collecting Information for KPIs

Part of selecting a KPI measure is to identify where the ongoing performance data will come from, how it is collected and when. If the data is not currently collected someone will need to be appointed to gather it and provide it in a suitable form.

Usually the clerical function of compiling data delegates to a lower level employee than those using the KPI. It is critical that they are given the time to properly collect the information, collate it correctly and believably, then provide it in a usable form to put straight into the KPI. In some cases a manager may collect data themselves in order to get a fuller understanding of what is truly happening. Finding the facts for oneself is to be encouraged. When determining a KPI it is critical to record the causes of discrepancies and problems, along with the frequency of their occurrence. The purpose of a KPI is to highlight a problem and decide if it needs removing. That means capturing the problems and their effects to quantify and cost their consequences. Each of the causes can then be analysed for their impact on the operation and plans can be developed to address them based on their priority and urgency.

Creation of numerical data is normally easy, as performance figures and completion dates are usually required on many organisational reports. Collating the data into a usable form can be expensive and time consuming where no such systems presently exist. Where completely new data is required, there needs to be a great deal of planning and preparation done to introduce the new data collection requirements and methods into the current work processes. Because of the disruption and start-up errors that will occur, it is preferred to work with data already available in an operation than introduce additional data collection. However, if the importance of the data is critical to the future success of the organisation, then its inherent value justifies making whatever changes are necessary to allow the collection of the relevant information.

You can reduce time recording and recovering data by introducing computerisation into the lowest level of the organisation where the data comes from. By computerising data collection it is quicker and simpler to gather it and to interrogate its contents. It also allows development of various KPIs presenting different information from the same records.

Data Integrity

The data you use in KPIs must be unquestionably correct. Collecting data is easy. Collecting data that is a true reflection of what actually happens is much harder. It is critical to ensure that the information collected is actually used in creating the KPI. Collecting unnecessary or wrong information is a complete waste of time, people and money. The stories of monthly reports generated and not actually used by anyone are common in too many organisations.

Issues of data integrity require managers to specify exactly what information is to be gathered and how it displays. It is not a clerk's role to ensure the KPI information is the correct one to use in the first place. The manager is responsibility to set up the KPI system, to define the parameters to measure, and to specify the base data needed to develop the KPI. The clerk is only responsible to follow the specifications and requirements put in place by the manager.

Industry Data

KPI's that are trended against benchmarks require a benchmark to be established. The benchmark figures come from industry and corporate bodies or professional organisations. Another source can be bureaus of statistics or recognised data collection organisations.

Best in Class Data

When organisations are striving to improve themselves and move toward best-in-class performance it is necessary to know the best-in-class results. Specialist consultancies that conduct benchmarking are available and will provide the results for a fee. Possibly consultants with long and broad experience in an industry will know what world-class performance is for the industry. Occasionally the best in class measures are available at industry conventions and presentations. Usually copies of white papers are available after the presentation. Other avenues to find best-in-class benchmarks include industry magazine articles and researching industry websites.

Self-Developed Data

In many cases you can develop KPIs to improve future results without reference to external parties or benchmarks. You select and apply KPIs that use existing data available to the organisation. If no appropriate data is present it must be developed and new collection methods and reports put into place.

Frequency of Data Collection

How often do you need to collect KPI data? Your answer to that question will define how much time and resources to put into developing your KPI system and its reports. KPIs measuring a time component will require a collection frequency to match the time parameter – minutes, hours, days, weeks, months and years.

The amount of data generated for a KPI is proportional to its reporting frequency and the volume of data provided. You will need suitable storage capacity and access to the records required. You will also need people with the time and skills to develop the associated reports and charts by the reporting date.

Presenting KPI's – make them visual

A KPI can be as simple as a single number, through to multiple lines on a graph, or strings of results in a table. KPI reports can be a single page in length, through to a multi-page document. Where possible it is best to present KPI results in a graph. Human beings receive most sensory data through their eyes. Our brains are excellent at detecting changes and variation. But the brain can handle only 5 or 6 pieces of information at one time. These natural traits make graphic formats using colour, contrast and clarity preferred to using numerical lists. As well as showing the current KPIs, the presentation must also show either historical trends or the benchmark target. It is only by comparing the reported value against a known performance that a true comparison of achievement can be made. Three of many ways to present KPI trends are in Figures 16.8, 16.9 and 16.10.

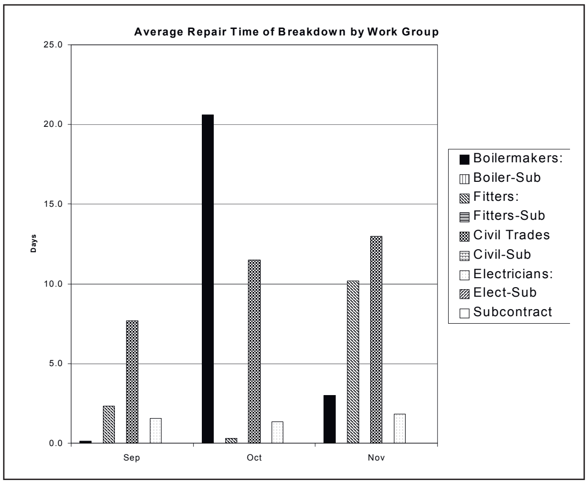

Figure 16.8 – Bar Chart of a Long-Term Continuous Improvement Initiative.

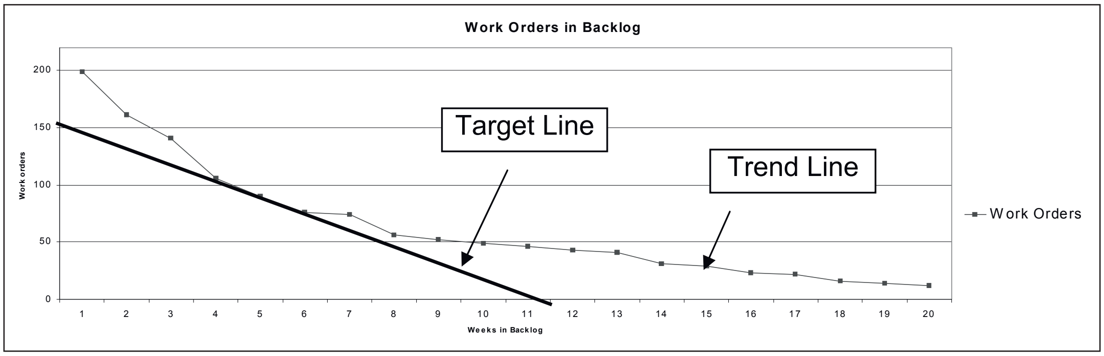

Figure 16.9 – Trending Graph Showing Current Performance against Target.

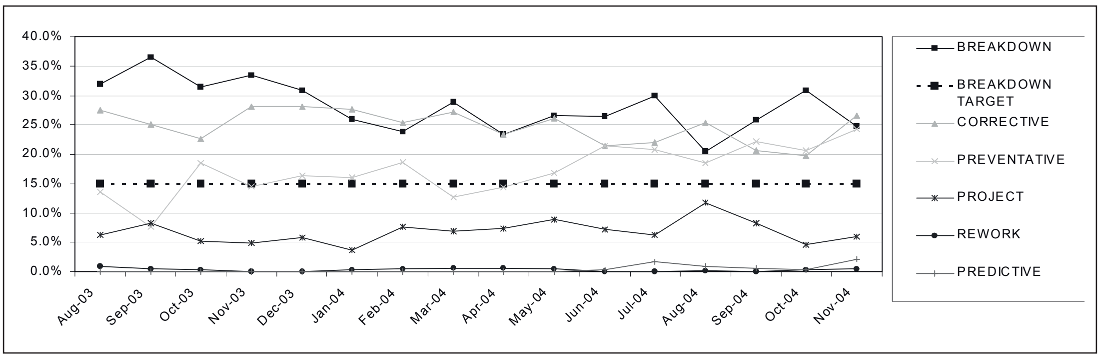

Figure 16.10 – Trending Graph Showing Multiple KPI's on One Graph Including Targets.

How to Use Key Performance Indicators

Key Performance Indicators trend performance. Performance is the result of actions taken, and actions are the result of decisions made. You use KPIs to help people make decisions, or to check on the effect of the decisions people have made. A KPI will tell you if the decisions taken and the subsequent actions have produced a change. Hopefully the change has been beneficial.

KPIs can be used to aid in improving the decision-making of all your people. Make KPIs available to all persons who can gain benefit from knowing the result. People will self-correct and adjust their practices based upon the KPI. It may require some time for some people to change their work methods and practices. In such cases continue pointing out that no beneficial change has yet occurred and that is unacceptable for the future wellbeing of the person, workgroup, department or organisation.

If a KPI result is not an improvement your people will take that to heart and begin looking for ways to better the result next time. This requires encouragement and the opportunity to discuss ideas that will bring about improvements. Make time to let everyone affected by the need for a change to be involved in deciding how to make the change. If they are not involved they will unconsciously block the efforts of others. A participatory approach has a better chance to get commitment and acceptance from all than forcing change on people. It will also be the quickest way to find a good, lasting solution to the issues. If the result is on or above expectation your people will see it as an endorsement of their efforts and want to continue and improve what they do. Reward people proportionate to the progress made.

Managing Performance with KPI's

KPIs are used to purposely feedback and feed-forward critical information in a timely manner to make changes in a process. Without KPIs monitoring a process, the process is not in control. A process can be horribly inefficient and ineffective, terribly costly to the organisation, but still performed continually because there are no measures to judge the worth of its results. KPIs provide a check on progress, they provide direction and they provide data to make sound decisions.

Once there is a KPI there will be people responsible for its attainment. A KPI reflects performance. Some people fear under-achievement, while others will see the KPI as a challenge to make them strive. The proper use of KPIs is not to cause pain to people but to help them to find ways to improve the process they are in charge of so that it produces the required results. KPIs bring a means to measure the effects of actions performed in a process. If the actions do not deliver the required results then scrutinise and review them to determine what part of the performance was not effective. With the issues identified, there needs to be an action plan, with time limits and individual responsibilities, put into place to rectify the situation.

Realise that KPIs will cause changes in people's behaviour. Recognise the good changes and the people who lead them. Recognise the group if success was a group effort. Be fair in your reward and spend according to the benefit the change has brought the organisation. Bad behaviours also need identification and their effects made public so that all can learn from them. But do not publicly punish the individuals involved in poor behaviour or performance, deal privately using support, encouragement and training to develop the appropriate behaviours. If in the end the individual is clearly unsuited to a task you need to move them into work in which they can excel.

Introducing KPI's into the Workplace

When introducing KPIs into a workplace it is necessary to explain their purpose, the workplace changes that may result from them, and the input required by the people in the workplace to collect them and manage to them. People will have a natural concern with changes in their workday and workplace. Most people want improvement and they will accept changes that they believe will help the organisation or themselves. When introducing KPIs talk about the improvements and benefits they will bring. Privately, openly and truthfully explain to each person impacted by the KPI – whether collecting the data, analysing the data or managing by the KPI – the specifics of how the KPI is used and the effect it could have on them. You want their acceptance and support in using the KPI and you will most likely get that if they are fully aware of how it impacts them.

Anytime there is hesitation with the use or introduction of KPI reporting it is best to request a trial period, after which there is a final assessment made on its continued use. The trail period should be a minimum of six reporting period's duration. By then people will have been through the introduction phase and started to realise the value of the KPI, if there is any.

KPI Alignment

To get the greatest benefit from using KPIs it is best to align them so a KPI acts to direct and reinforce common goals and purpose. The KPIs should cascade down from Organisational, to Departmental, to Work Group and finally to the Personal level. In this way everyone works toward the same aims. To help explain where they fit in the business show the KPIs in the organisation as a hierarchy from top to bottom.

That does not stop the use of KPIs to detect problems and resolve them. KPIs for that purpose are often temporary and only used until the issue is addressed. KPIs that drive an organisation are comparatively permanent and in use for many years. When an organisation's needs change the KPIs also change to match the new focus and direction.

Organisational KPIs

At the organisational level KPIs meet stakeholder requirements and corporate goals. Organisational KPIs can be a mix of financial, community, governmental and operational measures that track performance against set targets. These KPIs reflect the entire organisation's performance. The KPIs are a compilation of many factors and influences. A good structure for an organisational KPI is one that hierarchically subdivides into its component parts. These components allow further breakdown and analysis. By delving deeper through the make-up of the KPI it should be possible to highlight the problem factors and isolate them for closer investigation.

Each department, workgroup and individual should be producing outputs in-line with the organisation's goals. If the KPIs cascade down from the highest levels of the organisation to the lowest then alignment and shared focus is present throughout the operation.

Department KPIs

Departmental KPIs typically are about efficient and effective use of available resources. They highlight opportunities to improve and streamline processes. They also can act to increase 'silo mentality' and drive one department to damage the performance of other departments as they strive to reach their targets. This was one of the effects that the late W. Edwards Deming wanted to remove with his 14 Points of Management.

Work Group KPIs

KPIs applied to a work group focus the group on working together to achieve a suitable level of performance. They act to promote team work and higher efficiency amongst team members. They also can act to increase 'silo mentality' and drive one work group to damage the performance of other groups.

Personal KPIs

The purpose of KPIs used to manage at a personal level is to guide individual performance. For the KPI to be valid the outcome must be under the control of the individual. Typically, factors such as time, throughput, quality, frequency, accuracy, cleanliness, safety, time keeping, etc. are the responsibility of the individual. By selecting suitable KPIs the individual is aware if their performance meets the necessary standard.

Be cautious with using personal KPIs. It is unfair and useless to attribute system results to individuals. Only special cause issues maybe due to a person. All common cause problems are due to the system and these cannot be changed by an employee, they are the sole responsibility of management to address [70].

Sample Maintenance KPIs

Table 16.1 lists a range of KPIs commonly used in maintenance management to track performance and trend progress of improvement efforts [71].

Table 16.1 – Maintenance Key Performance Indicators.

Overall Measures	Percent Uptime Total Maintenance Cost (TMC) as a % of Estimated Replacement Value
Reliability of Equipment	Reliability Professionals per Maintainer Mean Time Between Failure (MTBF) % Emergency Work Estimated Replacement Value (ERV) / Maintainer Training Days (Development/Refresher) / Maintainer
Quality and Speed of Execution/Response	Maintenance Work Force Weeks Backlog Percent Planned Work Maintainers per Planner Schedule Compliance
Maintenance Costs	Stores Investment as a Percent of ERV Percent Overtime Maintenance Labor Cost as a Percent of TMC Contractor Maintenance Labor Cost as a Percent of TMC
Prediction of Failure	Percent PPM Work Percent PPM Schedule Compliance Percent Emergency Work

70 Deming, W. Edwards, 'Out of the Crisis', MIT Press, London, England, 2000 edition.
71 Maximising Operational Efficiency Presentation, E. I. Du Pont de Nemours and Co, 2004.

17. Mining Your Maintenance History

This chapter shows you how to take the data collected in your maintenance work order system and refine it, then analyse it and liberate the hugely valuable information it contains. Once you find and understand the precious information in your maintenance work order history you have the facts needed to solve your equipment reliability problems and deliver improved production performance. The information you find when you interrogate maintenance history lets you highlight new business opportunities and new means of plant and equipment improvement. For example, you could use the information to draw attention to better ways to design and select equipment, or purchase and manage spares, or to identify job planning loop-holes that could be improved to make work more efficient.

It is likely that you will want to re-design a lot of your equipment. You may even decide to re-engineer your production processes and your business systems once you discover what they have done to your business. It is almost certain that your maintenance work orders contain many opportunities to discover new ways to solve long-standing equipment problems and improve production plant operation. The information you unearth can enrich your people and your company in a positive fashion. Use the information to get the management and financial support you need to change for the better.

Why Analyse Your Maintenance Work Orders

A good maintenance work order report has the history of the maintenance job, the parts used, a record of the damage, and the associated costs and resources used on the job. With cost data, work-time data, resources data and operating-impact data, you have the information to measure productivity, efficiency, value-add and effectiveness of the maintenance effort on the operation. These are operating performance measures of powerful value for any business. They become accessible by first collecting, and later interrogating, your maintenance work order histories. If you have a collection of complete and accurate maintenance work order history spanning long periods, you have good information to measure the worth of that maintenance to the organisation. You also have a complete list of all the maintenance and reliability problems in your operation. Provided your maintenance system records the full costs, resources and times needed to do a maintenance job, you can be confident that the information drawn from it will reflect the truth. The work order history is a factual data base that through careful analysis lets you identify opportunities to solve equipment problems and improve current operating and maintenance practices for the betterment of all concerned. By analysing maintenance work orders you can detect hidden trends. Such as an increase in breakdown work, or a rise in costs compared to previous periods. There are numerous messages about the operation, the equipment, and their performance hidden in your work order system. Even if your maintenance work order system only records the repairman's report there is still enough information there to let you identify equipment reliability problems and justify their solving.

How to Analyse Your Work Orders

Analysing maintenance work orders (MWO) involves searching for themes and patterns in their history. One-off variations in maintenance jobs where a thing did not go well, or there were errors made, are not useful for changing the philosophy of doing maintenance (unless many of your maintenance jobs keep going bad; then you have a business system issue to solve quickly!).

Maintenance work analysis uses historical work orders from a particular period and specific facility area, or process circuit, or manufacturing line, etc. By using data over a reasonable length of time the effects and trends, and perhaps even their causes, become evident. It is the trends that are important, as they reflect the persistent factors in your 'system' that impact on it over the long-term. If there are systematic problems you need to identify them and correct the business system, since it is because of the business system that you have the problems. Occasional repairs that go over the expected cost will not send you broke. What will send you broke is a business system that does not recognise what causes the costs and has nothing in-place to control those causes. If the maintenance system itself is a failure then you need to recognise that from your maintenance history and move to fix it quickly!

Periods to Use for Analysis

Typical time periods used are the financial year or the calendar year. Other useful periods are financial quarter or calendar quarter, particularly if you are looking for evidence of short-term performance changes. Long-term periods include 2, 5 and 10 years. These are good for investigating equipment reliability issues, or the long-term effect of changes in methods and philosophies applied in the organisation. One means to view these long trends is with the 'Long-Term Improvement Plan' spreadsheet provided on the CD accompanying this book. Its purpose is to show a historic record of the frequency of problems and their impact on the operation over the years. It provides evidence to justify their removal by redesign or the purchase of more reliable equipment. Future improvement projects are included on the spreadsheet to show a business' commitment to expend resources and capital to make the operation more reliable and lower cost. When analysing specific items of equipment the period can be the equipment's entire working life. This may span several decades. If during that time the equipment was improved, the analyst needs to know, so they are aware when the history altered because of the improvement. Otherwise, they may use the maintenance history incorrectly and advise that a problem exists when it does not.

The easiest way to interrogate historical work orders is to place all the records over a period from a section of facility into spreadsheet software. If the maintenance work orders are in electronic form exporting the data into a suitable spreadsheet is normally a straight-forward task. Where the maintenance work orders are in a manual system get the necessary information entered into the spreadsheet. Record the work order data in spreadsheet columns suitably titled for the information. Typical headings include equipment number, equipment name, work order number, trades required, date requested, date completed, job description, job history or corrective action, material costs, labour costs, resources costs, along with other relevant information related to the analysis. A simple example of such a spreadsheet is Table 17.1.

If you are still using a verbal request system for maintenance work the analysis is much more difficult and less meaningful. However, it is possible to do a basic level of analysis by interviewing your operators and maintainers. Taking equipment items one at a time and then their assemblies and components one at a time, record peoples' recollections of problems over the years and the maintenance done to fix them. Develop the analysis categories you require before the interviews so that you know what questions to ask them. Another useful repository of plant and equipment history are the operations and maintenance shift logbooks used to record daily issues and to communicate between people and shifts. Read these carefully looking for equipment problems and dates and describe the details in the spreadsheet.

Using Existing Categories on the Maintenance Work Order for Analysis

Usually a maintenance work order has a range of information recorded on it as it moves through the maintenance process from generation to performance and finally closure. This information allows the work order to be analysed by those categories. When transferring the data from the work order system into a spreadsheet make sure that data names, or titles, come across with the data and are put as the column headings of the spreadsheet. Without the column headings you will not be able to recognise what the data represents. Hide unnecessary columns in the spreadsheet in order to show only the columns you require. It is more convenient to hide columns instead of deleting them so that a column is available for a later analysis if necessary. Once you delete a column the data is lost and you must start the spreadsheet again if later you find you did need the information.

Introducing New Analysis Categories and Codes

At times, the work order may not have the search criteria you want to use as one of its standard fields. In such situations it is necessary to introduce the category you require into the spreadsheet with its own column. You then go through each work order one by one and categorise it by the new category. For example, Table 17.2 introduces two new columns into the spreadsheet for two new categories – Job Type and Work Order Cause. The two new categories are themselves divided into a series of meaningful codes. The Work Order Cause Category codes consists of:

P – Process related cause where the work order was a result of a process problem.

D – Design related causes where the WO was most probably due to a design decision.

I – Installation related cause from poor installation practices.

M – Maintenance related causes due to real maintenance issues.

O – Operating related cause from operator errors.

S – Statutory requirement that require maintenance by law.

E – Else causes where no obvious explanation was evident.

The Work Order Cause category designates each work order by the likely reason for its raising. It highlights that a good proportion of maintenance was due to design, installation and operating issues that then flowed onto cause maintenance costs. A lot of your maintenance cost is most likely not due to the equipment, but from knock-on effects caused by other reasons.

The Job Type Category codes covered:

R – Regular and normal maintenance work that is fair and reasonable to expect.

I – Improvement to plant or capital project related work.

F – Failure and breakdown repair related work.

A – Assistance provided to operations work but not related to maintenance.

P – Preventative related works, which were usually PM's and statutory jobs.

The Job Type category allows the work orders generated in the plant to be analysed to determine how much of the work performed by the maintenance group was truly a maintenance cost. A lot of your maintenance costs may not be strictly maintenance. Rather your maintenance crew do non-maintenance duties that take up their time and their costs are booked to maintenance. Read each work order through and give a code to represent its category. The requirement to read each work order and select a code to classify it can take a great amount of time. Yet if you introduce new categories to classify the maintenance work orders, it makes sense to spend the time and effort to classify them correctly so that you get a good, reliable and accurate analysis. Once you have trustworthy information you will have the confidence to use it to make decisions.

The organisation decides and defines what extra analysis categories they need. The analyst doing the work needs to know the categories to use and the meaning of each code in the category. The

Table 17.1 – Example of a Basic Maintenance Work Order Analysis Spreadsheet.

Asset No	Short Desc.	work_grp	cmpl_date	labour	mtl_cost	con_cost	workreq	corr_action
WLW	Willow Hill Facility	CIVILS	26/08/04	$0	$1,281	$1,281	Please get the roof on the storage shed repaired/made safe as the clear cladding has become loose.	Skylight replaced
WLW	Willow Hill Facility	FITTERS	21/07/04	$170	$148	$250	Carry out lubrication round per attached route sheet	Replace 2 auto-lubes - topped up g/boxes
WLW	Willow Hill Facility	CIVILS	02/12/04	$255	$335	$488	Please get the plastic curtains on the storage shed repaired, some are loose, and one has come off.	As per work requested
WLW	Willow Hill Facility	BOILERMAKERS	04/08/04	$467	$340	$620	Can we please have some hose racks made up for behind Facility west wall.	50x6 ss flat bar brackets mounted to concrete base of wall. 6m 300mm cable tray hose rack
WLW	Willow Hill Facility	BOILERMAKERS	06/08/04	$117	$20	$90	Could we please have a small tool box fitted to the tower floor to store tools in safely, this is required by a hazard report.	Tool box was bolted to floor as requested
WLW	Willow Hill Facility	BOILERMAKERS	04/08/04	$233	$40	$180	We require a small steel cabinet made up and installed by the large roller door to put safety gear in (gloves and dust masks)	Cabinet made
WLW	Willow Hill Facility	ELECTRICIANS	12/08/04	$1,006	$110	$714	Please have the power point located below WLW-10 relocated to the west side.	Moved GPO to where operators required it.
WLW	Willow Hill Facility	FITTERS	29/07/04	$58	$94	$112	Can we please get the automatic grease cartridges on the whole of the crushing circuit checked and replaced if necessary	Replaced 2 cartridges
WLWAC-6A	Air Compressor	SUBCONTRACT	18/08/04	$83	$0	$270	Please service air compressor	Changed separator within compressor
WLWAC-6A	Air Compressor	FITTERS	20/01/05	$83	$0	$300	Please service air compressor	Assisted serviceman
WLWAC-6B	Air Compressor	FITTERS	15/07/04	$83	$0	$745	Service air compressor	Assisted contractor with compressor service

Table 17.2 – Adding Additional Analysis Categories For Work Order Interrogation.

Asset No	Short Desc.	work_grp	cmpl_date	WO Cause	Job Type	labour	mtl_cost	con_cost	workreq	corr_action
WLW	Willow Hill Facility	FITTERS	30/03/05	O	A	$85	$0	$0	Please remove the bank/spade that at the spool piece so we can begin to run directly from tank.	Fitted spool piece back on
WLW	Willow Hill Facility	FITTERS	29/03/05	P	A	$43	$20	$33	Please set up the hoses from tank to pump so we can bypass tank	fitted spool pieces and hoses
WLWAD-4	ADVANCED SCREW UNIT	FITTERS	22/03/05	O	A	$375	$0	$225	Can we please have the pins removed from the housing	removed pins turned upside down to allow flow
WLWAD-4	ADVANCED SCREW UNIT	FITTERS	01/12/04	O	A	$85	$0	$51	Get all the pins turned around in the morning.	Removed all pins around
WLWCF-3	Filter	FITTERS	05/05/04	O	A	$417	$60	$310	Can we please have the flexible shroud inside the filter replaced	FITTED NEW SHROUD
WLWCF-3	Filter	ELECTRICIANS	21/05/04	O	A	$85	$10	$36	Please re-fit encoder during outage and lock in place.	REATTACHED ENCODER
WLWCF-3	Filter	ELECTRICIANS	30/06/04	O	A	$128	$0	$77	Please have the cake thickness sensor adjusted to decrease the cake thickness.	ADJUSTED CAKE THICKNESS SENSOR AS REQUIRED BY OPERATIONS
WLWCF-3	Filter	ELECTRICIANS	01/10/04	O	A	$67	$0	$20	Move cake thickness to increase the cake thickness by about 20-30mm.	ADJUSTED CAKE THICKNESS BY 25MM APPROX
WLWCF-3	Filter	ELECTRICIANS	15/03/05	O	A	$260	$0	$156	Move the level switch for larger cake thickness by 30mm	ADJUSTED BY OPERATORS

person selected to read and classify maintenance work orders into new codes must know the plant and equipment maintenance history very well. It requires a thorough knowledge of the equipment and the maintenance practices in your organisation for the correct classification of work orders into new categories. Typically this is someone like an experienced maintenance supervisor or even the plant engineer or maintenance engineer.

Conducting the Analysis of Your MWOs

The first step in analysis is to decide what you are looking for. You develop the spreadsheet structure to suit the questions you need to answer. When you know the questions you want answered you will extract the right information from your Computerised Maintenance Management System (CMMS), or manual systems, into the spreadsheet. You can also add any missing categories needed to analyse the spreadsheet data. Once the maintenance order history is listed under the headings you require, use the sorting functions of the spreadsheet package to collect and arrange the data into meaningful sense. You will need to know the appropriate spreadsheet software instructions. Some common questions include:

a) What proportion of maintenance work is breakdown, corrective, preventative, etc?
b) How often is an equipment item failing?
c) What is causing the maintenance required? (Here you develop meaningful codes to use when categorising the work orders)
d) What parts are regularly replaced?
e) What outside services and contractors are regularly hired?

The range of questions is dependent on the data available for analysis. Questions involving parts usage or subcontractor hire require access to information in inventory management and purchasing systems. It may be more beneficial to use other data bases and information systems if they are better suited to the query. It may not be sensible to find answers to questions through MWO history analysis if the relevant data is already in other parts of your management information systems.

Identifying Reoccurring Problems and Opportunities to Improve

It is important to know how well directed the maintenance efforts are, or if they can be more finely tuned. Analysis of categories such as costs, times, maintenance problems, etc will draw attention to hidden issues. Sorting a spreadsheet by category and category code captures work orders of the same code and identifies them as having a common reason to be in the group. The category code represents an issue that you are interested in knowing about and identifies work orders related to that issue. Once the work orders are coded you review each for additional insights into the specific issues related to the code group. It may take a substantial amount of time, possibly days, to conduct a truly thorough analysis. You will later recover the cost of the time invested with the improvements that will flow from the analysis. The effort to understand maintenance actions and effects, and to look for ways to improve equipment care, delivers paybacks for years to come in streamlined processes, improved equipment performance and higher rates of production at lower costs [72].

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[72] Fitchett, Don, Sondalini, Mike, 'True Downtime Cost', 2nd Edition, www.BIN95.com, 2006.

Keyword Searching

An alternative to the use of categories and codes is to use the existing text on the work order and search for keywords within the text. For example, searching for 'bearing(s)' in the work order text will identify those work orders where the word appears in the text. If there were many references to bearing problems for an item of equipment then you would have justification to investigate the causes and look at solving them. The information may support spending money to improve the lubrication program or change machine bearing protection. The keyword search approach is most often fruitful in work request description text and the job completion comments from the repairman. Identifying maintenance issues through work order keyword searching can highlight hidden equipment and system problems not previously recognised because they occurred infrequently.

Pareto Charting the Frequency of Repetitive Problems

Maintenance work orders can be categorised by the frequency an issue arises and shown in a Pareto chart to highlight their occurrence. A Pareto chart makes issues visible. They work for individual equipment or for entire processes. Figure 17.1 is an example for the diaphragm pump operating problems from Table 17.3. The Pareto chart highlights that the pump was changed-out numerous times and there were blockage problems with the process. These types of analyses are ideal for identifying repetative problems that an operation is living with.

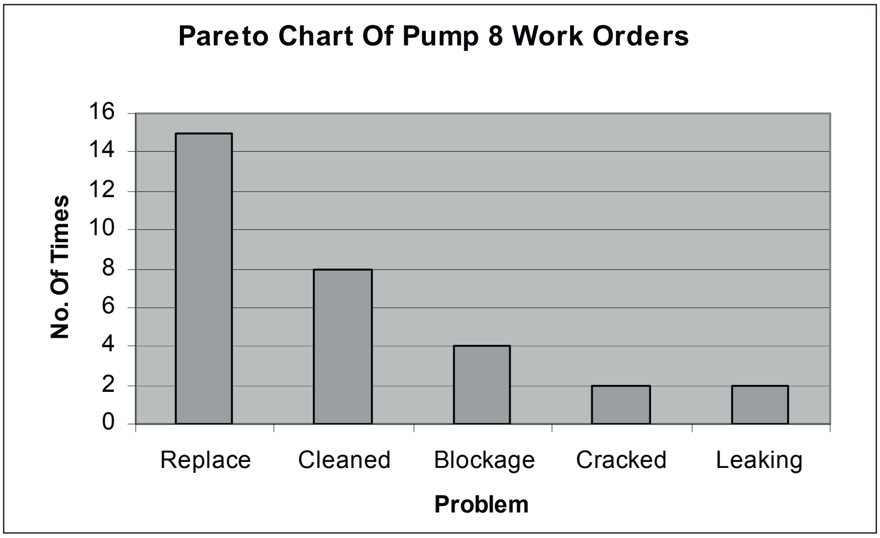

Figure 17.1 – Pareto of Diaphragm Pump Failures.

A Pareto chart could compare costs per repair, hours to repair, or any other category on the spreadsheet. How the data should be analysed for information and understanding of the issue is entirely up to the analyst in response to the investigation brief.

Timeline Frequency Analysis (Charting Time Between Failure)

A Time Series Table, like Table 17.4, involves looking at the dates of work on equipment and laying out the dates for repetitive work orders in horizontal rows for all to see. The process of building the Time Series Table is straightforward. Choose the category of interest or categorise the work orders by category, then record the work order start dates in a row of the spreadsheet. Gradually you see the scale of the problem by the number of entries on the rows and the frequency of the problem by the number of repair dates. You can go a step further and find the direct costs of living with the problem. If the work orders record cost information it is a simple matter to collect the total costs for each work order and tally them to present a very clear picture of the direct expense of the problem. (The cost on a work order does not include the full DAFT Cost to the organisation. Until all DAFT costs are included in the costing exercise you do not yet have the true downtime cost to the business.)

The issue dates and completion dates used on work orders are useful for identify the failure frequency for a plant item. Table 17.5 shows the completion dates rearranged in calendar order, and the days between each work order. The 'Days Between' failure column is also shown as a time series in Figure 17.2. As a plot it is visually graphic and attention grabbing. This item of plant clearly caused a great deal of trouble for the operation throughout its operating life. In one case, it failed three times on the same day! The history of failure makes it clear that the problem is an operating issue where process material blocks the pump. Changing the pump with a spare was the solution most often taken. But the frequency of failure is so extreme that the problem was important enough to design-out of the process and a straining screen was installed to catch solids. Using a timeline lets you highlight the real impact of a problem's frequency. If failures are excessive or expensive this analysis strikingly identifies need for improvement.

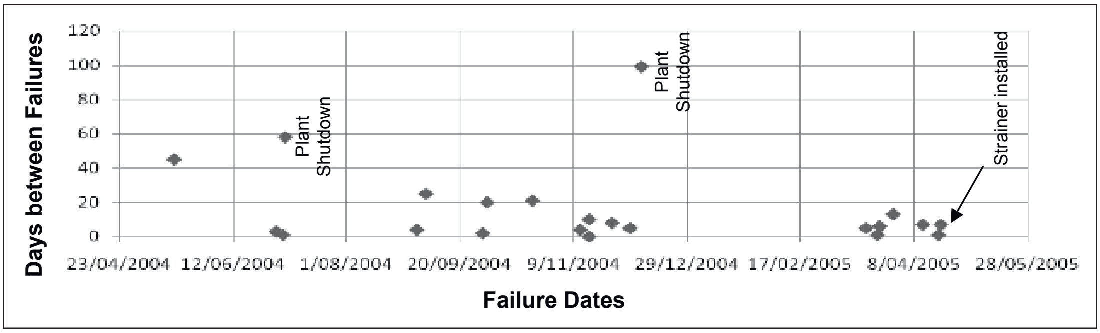

Figure 17.2 – Failure History Timeline.

Ratio Comparisons for Benchmarking and Continuous Improvement

With all work orders for a period and/or item of plant gathered in a spreadsheet it is opportune to develop management ratios of operational and equipment performance. The choice of ratios and their aim is up to the organisation's management. They can be used to benchmark against others in your industry or as a means to track your continuous improvement. Ratios include:

$$\text{Breakdown Ratio} = \frac{\text{Breakdown WOs}}{\text{Total WOs}}$$

$$\text{Preventative Maintenance Ratio} = \frac{\text{PM WOs}}{\text{Total WOs}}$$

$$\text{Proportion of Time Maintaining} = \frac{\text{Total Time Spent on Maintenance WOs}}{\text{Total of Time for Maintenance Crew}}$$

$$\text{Use of Contractors Ratio} = \frac{\text{Total of Contractor Time on WOs}}{\text{Total of Time on All WOs}}$$

Any analysis category would make useful key performance indicator ratios if improvements were to be undertaken. Two examples might be:

$$\text{\% MWO's Due to Design Problems} = \frac{\text{No. of WOs Attributed to Design Issues}}{\text{Total WOs}}$$

$$\text{\% MWO's Due to Operating Errors} = \frac{\text{No. of WOs Attributed to Operator Error}}{\text{Total WOs}}$$

Analysing Equipment Reliability Issues

Another way to analyse MWOs is by taking one item of equipment and reviewing its maintenance history to focus on the issues affecting its performance. This allows you to identify what these issues are, their effect on the operation and their cost to production. For example, it may be useful to identify causes of repetitive failures, or why there are continual replacements of parts, and design-out the problem causing the maintenance. Once you have categories for the causes of equipment operating and maintenance problems you can develop solutions to address the worst of them. When investigating equipment reliability issues you require all maintenance history available on the item of plant from its start-up date, or for as long as there is history. Having equipment history that reflects the operation and maintenance of the equipment over a long time provides a good amount of factual data to work with. It will show any persistent issues that have been with the equipment during its life.

Table 17.6 is a spreadsheet for a centrifugal pump with persistent failures identified and classified over a year. They were due to three failure modes. One was dead-heading where a programming error closed the discharge valve when instructed by the process control computer but the pump ran-on and did not turn-off in the program. The second was where the operators ran the pump in manual to empty the tank and then left the pump running so that is was run dry and destroyed the mechanical seal. The third was a process problem where product scaled the impeller and suction entrance when the pump stopped and jammed the impeller in place. It was only after analysing and putting a cost to the problems, identifying their production time losses and associated expenses, that the true production impact of the pump failures was recognised. Once it was clear that the failures were causing serious maintenance costs concerted efforts were made to stop the failures. Without the maintenance history data to provide evidence of cost and failure frequency, it would have been difficult to get production support to fix the real causes of the problems.

Identifying with Fault Codes

Each equipment failure will have a reason. It is important to find the real cause of the problem and fix it. Analysing maintenance work orders with fault codes is a powerful way to find failure problems. With the work order history in a spreadsheet you read each work order text, both the request and the repairman's report, looking for keywords related to the job. It soon becomes apparent what problems the equipment has suffered during its operating life by the continual use of the same words, or words of similar meaning, in the text. These problems become the fault codes to classify all work orders. An example of using identifying fault codes is Table 17.6.

If your MWO already contains fault codes as part of your standard procedures, still read a selection of about 20% of the work orders to see if the fault codes used are reliable and accurate. If they are not accurate then reclassify all the MWOs with apt fault codes.

To gain additional insights it is also valuable to read the maintenance crew logbooks and the operator or production shift logbooks for the period concerned. The operations logbooks and maintenance crew shift records can contain valuable details on problems that were not recorded in the maintenance work order history. This information can be of great use in understanding what process problems, operating problems and shift crew problems existed prior to equipment failures.

Analysing Equipment Reliability

If a part or equipment item is failing too soon you investigate the reason. Provided there are reliable dates of failures for each failure mode, and no failures by a mode have been missed, it is possible to do engineering reliability on the failure. With each failure mode identified you have the necessary information to conduct reliability modelling and analysis to interrogate the failure modes so you can solve them.

Software programs are available to trend equipment reliability and develop probability of failure curves. For example, if you have parts usage dates of age-related failures the software can be used to determine the optimal period between parts replacement. The software optimises the cost and date to do preventative maintenance and advises when to replace the part to minimise downtime losses.

Before using reliability prediction software carry-out a timeline frequency analysis for each failure mode and see if the periods between failures already identify obvious problems for investigation. Use timeline analysis to identify when equipment is not providing sufficient service life. This stimulates engineering and management focus to make resources available to fix problems.

Reliability engineering is now a well developed discipline and a powerful additional tool available to understand what happens to equipment. There are serious pitfalls to be aware of in analysing equipment reliability and it is the realm of people well-educated in probability mathematics and trained in the use and limitations of the methods applied. Develop in-house university qualified reliability specialists or establish a contractual relationship with an experienced service provider. Chapter 18 provides a short introduction to Reliability Engineering.

Analysing Maintenance Costs and Time

Equipment maintenance costs are easily analysed once put into a spreadsheet. You can group costs by any category on the spreadsheet. If you want total costs for breakdowns and preventive maintenance on a machine during a particular period, you would sort the spreadsheet into those categories and subtotal the costs. An example is Table 17.7 showing subtotal costs for equipment. With subtotals by category you can proportion costs against total cost. For example, this can be the cost of equipment maintenance in one year against the cost for its lifetime, or the cost of preventive maintenance for the equipment in a period as a proportion of all maintenance spent on it in the period.

This approach is useful to analyse the repair time recorded on maintenance work orders (also known as Mean Time To Repair – MTTR). Long repair times mean equipment was not available for production. Where the average times to do a job vary greatly it justifies an investigation. Analysis of the work order times will identify problems and allow people to propose solutions for issues affecting the work.

One concern with using historic work order times is that unless people are paid on the times recorded on the work orders the times will not be accurate. They will be a rough estimate and not itemised by use of the time. When you analyse labour time data from maintenance work orders be aware that there will be inaccurate recording of the real times of all resources and labour used on the job. Provided you are willing to use the time analysis results as an indication of effort, and not an absolute measure, you may get some meaningful results.

Capital Justification Including True Downtime Costs

There will be many reasons for the problems discovered by your analysis. What is important is to find strong financial justifications to make the necessary changes to get rid of them. Improvements will only be supported by management if there is a strong financial case in their favour. As you do your analyses always keep the thought in the back of your mind of how to find the true and full costs that these problems are causing your organisation.

Your work order history should have records of all the costs incurred by the maintenance department during a repair. You will not have true costs if they don't include allowances for all the maintenance overhead expenses required to deliver maintenance. Costs for supervision, planning, management, accountancy support, payroll support, stores management support, etc, need to be recorded to each work order. If the maintenance cost is high enough it will justify investing money, time and resources to remove or reduce the problem.

The maintenance costs noted in the CMMS are not the true costs of a problem to your company. DAFT Cost analysis warns us that even if all overhead costs were included in a MWO it would still be short of the true business-wide cost by around 1,000%! The shortfall is the knock-on costs of failure incurred by the entire business. You may need to find them all to justify capital improvement or changes to business processes.

When preparing capital justifications to fix the problems discovered by your analysis you will be required to quote real, provable costs. These costs will be part of what you find as you do the analysis. But be sure that somewhere in your report you also tell readers about the other DAFT Costs that you could not find during your analysis. They are there, hidden in the business-wide waste caused by every failure.

Results from Case Study Investigation

Throughout this chapter the examples shown reflected a real analysis performed on an operating plant. The results of the study are summarised in Table 17.8. From it maintenance and process improvement strategies were identified to address the low plant reliability that was caused by the numerous random failures and poor manufacturing process control.

Table 17.3 – Identifying Causes of Failure and Showing Them in a Pareto Chart.

Asset No	Short Desc.	WO Cause	Job Type	Problem	workreq	corr_action
WLWPU-8	Cleaning pump	P	F	Replace	Please replace pump as it is not pumping.	removed pump and
WLWPU-8	Cleaning pump	P	F	Replace	CHANGE OUT PUMP 8 WITH SPARE	As Per Work Requested -
WLWPU-8	Cleaning pump	P	F	Replace	Please repair/ replace Pump 8 as it is not pumping.	Replaced Pump 8 with recon pump
WLWPU-8	Cleaning pump	P	F	Leaking	PUMP 8 is leaking can we please have it fixed.	REPLACE 1.5" BOLTS FOR 1.75" AS THE BOLTS WERE STRIPPED. PUMP IS TURNING OFF AFTER VALVE HAS BEEN CLOSED SEEN ELECTRICIAN ABOUT CHANGING PLC SO DISCHARGE V/V STAYS OPEN 5-10SEC LONGER.
WLWPU-8	Cleaning pump	P	F	Replace	REMOVE Pump 8 AND REPAIR OR REPLACE	REPLACED Pump 8 WITH SPARE
WLWPU-8	Cleaning pump	P	F	Blockage	REPAIR ON CHANGEOVER Pump 8	REMOVED BLOCKED PUMP AND INSTALLED RECON
WLWPU-8	Cleaning pump	P	F	Replace Cleaned	Can we please have stripped and cleaned out.	Pump 8 CHANGED OUT AND CLEANED PIPEWORK - STRIPPED PUMP
WLWPU-8	Cleaning pump	P	F	Leaking	PUMP 8 LEAKING AND NOT PUMPING PROPERLY - INVESTIGATE AND/OR REPLACE	REPLACED PUMP
WLWPU-8	Cleaning pump	P	F	Replace	Pump 8 not pumping, please inspect and repair/ replace	exchanged pump - cleaned pipe work
WLWPU-8	Cleaning pump	P	F	Cracked	PUMP 8 is cracked can we please have it changed out.	
WLWPU-8	Cleaning pump	P	F	Blockage	check Pump 8 and associated pipe work for blockage	REPLACED PUMP AND CLEANED PIPEWORK
WLWPU-8	Cleaning pump	P	F	Blockage	Pump 8 is blocked/not working and the bottom of tank 8 is full of hard solids. Please remove and repair the pump and make it possible for the operators to clean out the bottom of tank 8.	As Per Work Requested
WLWPU-8	Cleaning pump	P	F	Replace	Please order a new PUMP 8	allow 2 weeks delivery
WLWPU-8	Cleaning pump	P	F	Replace	PLEASE REPLACE Pump 8	Relocate old pump and install. Check suction lines - clear.
WLWPU-8	Cleaning pump	P	F	Replace	PUMP 8 is not pumping, can we please get this fixed/replaced.	As Per Work Requested
WLWPU-8	Cleaning pump	P	F	Cleaned	PUMP 8 is not pumping can we please have it fixed or replaced.	Stripped pump once removed cleaned out and refitted
WLWPU-8	Cleaning pump	P	F	Blockage	PUMP 8 is blocked up again and TANK 8 is overflowing. Please inspect and repair.	Change out pump
WLWPU-8	Cleaning pump	P	F	Replace	Can we please get Pump 8 changed out.	As Per Work Requested
WLWPU-8	Cleaning pump	P	F	Cleaned	Pump 8 is not pumping can we please have it fixed can we also have the top of TK-8 removed as it is full of solids.	STRIPPED PUMP 8 CLEANED REBUILT
WLWPU-8	Cleaning pump	P	F	Replace Cleaned	Pump is not pumping properly can we please have it looked at.	REPLACE WITH RECON PUMP - CLEANED OLD PUMP
WLWPU-8	Cleaning pump	P	F	Replace	Can we please get PUMP 8 changed out	changed out pump and replaced with recon
WLWPU-8	Cleaning pump	P	F	Replace	Can we please get PUMP 8 changed out as it is not pumping correctly	changed out Pump 8
WLWPU-8	Cleaning pump	P	F	Replace	Tk-8 is overflowing again. Please replace Pump 8 and clean out tank 8.	REMOVED PUMP 8 - REBUILT.
WLWPU-8	Cleaning pump	P	F	Cracked	repair to Pump 8 cracked and leaking badly	As Per Work Requested -

Table 17.4 – Time Series Table Using The Work Order Creation Dates.

Asset No.	Equipment Description	Work Order Description	Work Order Creation Dates													
WLWBN-41	Product Bin	replace dust bags	Apr-03	Oct-03	Nov-03											
WLWBN-42	Product Hopper	bagging head valve not operating	Dec-03	Jun-04	Jul-04	Aug-04										
WLWCF-3	Screen	remove and unblock feed pipe	Mar-03	Mar-03	May-03	Jul-03	Feb-04									
WLWCF-3	Screen	fix/adjust level setting	May-03	May-03	May-03	Aug-03	Aug-03	Aug-03	Sep-03	Sep-03	Oct-03	Oct-03	Nov-03	Nov-03	Feb-03	Mar-05
WLWCF-3	Screen	clean/replace spray nozzles	May-03	Jul-03	Jul-03	Aug-03	Aug-03	Aug-03	Sep-03	Oct-03	May-04					
WLWCF-3	Screen	adjust cake level sensor	May-03	Mar-04	Jun-04	Oct-04	Mar-05									
WLWCV-11	weigh feeder to mixing tank	VSD tripped, reset drive	Mar-03	Mar-03	May-03	May-03	Jun-03	Jun-03	Jul-03							
WLWCV-11	weigh feeder to mixing tank	seal leaking on hopper	Feb-03	Nov-03	Dec-03											
WLWDR-4	paddle unit	inspect, clean air ductwork	Apr-03	Jun-03												
WLWDR-4	paddle unit	unblock pipe work from dust collector	May-03	Jun-03	Jun-03	Jun-03										
WLWDR-4	paddle unit	replace gasket/seals on steam line	Aug-03	Nov-03	Dec-03	Jan-04	Apr-04	Apr-04	Jul-04	Aug-04	Aug-04	Oct-04	Mar-05			
WLWDR-4	paddle unit	bearing replaced	Aug-04	Aug-04	May-05											
WLWEV-6(HE)	Heat Exchanger	Replace heat exchanger	Mar-03	May-03	Nov-03	Oct-04										
WLWEV-6(PU1)	Liquor Recycle Pump	Repair/Replace seal	Feb-03	May-03	Jul-03	Mar-04	Jul-04	Jul-04	Aug-04	Mar-05						
WLWEV-6(PU3)	Product pump	Repair/Replace seal	May-03	Nov-03												
WLWEV-6(VP1)	Vacuum Pump	Replace seal	Jun-03	Apr-05												
WLWFL-2A	Leaf filter unit	Low level sensor faulty	Mar-03	Mar-03	Jan-04	May-04										
WLWFL-2A	Leaf filter unit	Seal replacement	May-03	Aug-03	Oct-03	Apr-04										
WLWFL-2A	Leaf filter unit	clean, inspect pipe for blockages	Feb-03	Mar-03	Apr-04											
WLWFL-2A	Leaf filter unit	replace filter leaves	Jan-04	Feb-04	Apr-04											
WLWFL-2A	Leaf filter unit	Drain ball valve replaced	Apr-04	Jan-04	Dec-04	Jan-05										

Table 17.5 – Timeline Frequency Analysis or Mean Time Between Failure (MTBF) Charting.

Asset No	cmpl_date	workreq	corr_action	Dates in Order	Days Between
WLWPU-8	04/12/04	Please replace pump as it is not pumping.	removed pump and	17/05/04	0
WLWPU-8	05/07/04	CHANGE OUT PUMP 8 WITH SPARE	As Per Work Requested -	1/07/04	45 (Annual shut)
WLWPU-8	19/04/05	Please repair/ replace Pump 8 as it is not pumping.	Replaced Pump 8 with recon pump	4/07/04	3
WLWPU-8	01/07/04	PUMP 8 is leaking can we please have it fixed.	REPLACE 1.5" BOLTS FOR 1.75" AS THE BOLTS WERE STRIPPED. PUMP IS TURNING OFF AFTER VALVE HAS BEEN CLOSED SEEN ELECTRICIAN ABOUT CHANGING PLC SO DISCHARGE V/V STAYS OPEN 5-10SEC LONGER.	5/07/04	1
WLWPU-8	17/05/04	REMOVE Pump 8 AND REPAIR OR REPLACE	REPLACED Pump 8 WITH SPARE	1/09/04	46
WLWPU-8	04/07/04	REPAIR ON CHANGEOVER Pump 8	REMOVED BLOCKED PUMP AND INSTALLED RECON	5/09/04	4
WLWPU-8	01/09/04	Can we please have stripped and cleaned out.	Pump 8 CHANGED OUT AND CLEANED PIPEWORK - STRIPPED PUMP	30/09/04	25
WLWPU-8	05/09/04	PUMP 8 LEAKING AND NOT PUMPING PROPERLY - INVESTIGATE AND/OR REPLACE	REPLACED PUMP	2/10/04	2
WLWPU-8	02/10/04	Pump 8 not pumping, please inspect and repair/ replace	exchanged pump - cleaned pipe work	22/10/04	20
WLWPU-8	16/11/04	PUMP 8 is cracked can we please have it changed out.		12/11/04	20
WLWPU-8	30/09/04	check Pump 8 and associated pipe work for blockage	REPLACED PUMP AND CLEANED PIPEWORK	16/11/04	4
WLWPU-8	22/10/04	Pump 8 is blocked/not working and the bottom of tank 8 is full of hard solids. Please remove and repair the pump and make it possible for the operators to clean out the bottom of tank 8.	As Per Work Requested	16/11/04	0
WLWPU-8	12/11/04	Please order a new PUMP 8	allow 2 weeks delivery	16/11/04	0
WLWPU-8	16/11/04	PLEASE REPLACE Pump 8	Relocate old pump and install. Check suction lines - clear.	26/11/04	10
WLWPU-8	16/11/04	PUMP 8 is not pumping, can we please get this fixed/replaced.	As Per Work Requested	4/12/04	8
WLWPU-8	26/11/04	PUMP 8 is not pumping can we please have it fixed or replaced.	Stripped pump once removed cleaned out and refitted	9/12/04	5
WLWPU-8	09/12/04	PUMP 8 blocked again and TANK 8 is overflowing. Please inspect and repair.	Change out pump	18/03/05	95 (Plant was Shutdown)
WLWPU-8	27/04/05	Can we please get Pump 8 changed out.	As Per Work Requested	23/03/05	5
WLWPU-8	24/03/05	Pump 8 is not pumping can we please have it fixed can we also have the top of TK-8 removed as it is full of solids.	STRIPPED PUMP 8 CLEANED REBUILT	24/03/05	1
WLWPU-8	18/03/05	Pump is not pumping properly can we please have it looked at.	REPLACE WITH RECON PUMP - CLEANED OLD PUMP	30/03/05	6
WLWPU-8	23/03/05	Can we please get PUMP 8 changed out	changed out pump and replaced with recon	12/04/05	12
WLWPU-8	30/03/05	Can we please get PUMP 8 changed out as it is not pumping correctly	changed out Pump 8	19/04/05	7
WLWPU-8	20/04/05	Tk-8 is overflowing again. Please replace Pump 8 and clean tank 8.	REMOVED PUMP 8 - REBUILT.	20/04/05	1
WLWPU-8	12/04/05	repair to Pump 8 cracked and leaking badly	As Per Work Requested -	27/04/05	7

Table 17.6 – Spreadsheet Identifying Persistent Equipment Reliability Problems With Fault Codes.

Asset NO	Short Desc.	cmpl_date	WO Cause	Job Type	Failure Mode	workreq	corr_action
WLWPU-1	Mixing pump	14/05/04	P	F	Seized	Can we please have the wet end changed out during the shutdown as it is not freely turning on restarting	changed out pump with spare
WLWPU-1	Mixing pump	19/05/04	D	I		Replace existing pump suction spool with new double block and bleed spool	completed in shutdown
WLWPU-1	Mixing pump	16/07/04	O	F	Seal Leak	Please rebuild pump 1 as a spare	overhauled pump due to seal failure. had to realign concentricity from0.65 to 0.48mm mech seal failure due to broken stationary face, pump had been dead headed.
WLWPU-1	Mixing pump	14/05/04	O	F		The discharge ball valve has a bent shaft can we please replace	replace ball valve on pu-1
WLWPU-1	Mixing pump	08/07/04	M	P	Seal Leak	Inspect drive belts and check for burning, fraying or cracking. Replace if required Inspect dive pulleys for wear Check alignment of pulleys and belt tension. Realign and retention if required	This PM not done since pump changed out 6/07/04 due to mech seal failure
WLWPU-1	Mixing pump	07/07/04	M	P	Seal Leak	The seal on PU1 is leaking badly, can we please have this changed out tomorrow while the cleaning circuit is depressurised.	Mech seal failure
WLWPU-1	Mixing pump	06/10/04	P	F	Seized	PU-1 will not turn fix it.	freed up pump with stilsons
WLWPU-1	Mixing pump	22/12/04	O	P	Seized	PU-1 will not turn, it appears to be seized, please get this fixed	pump and line not drained after use - pump freed up
WLWPU-1	Mixing pump	15/02/05	M	F	Seized	WHPU-1 has tripped and will not reset (might need fitter as support)	check motor history code indicates thermal o/l possibly due to ambient temp. reset running ok - tripped again thermal o/l. current tripping rated limit. suspect impeller. fitted recon pump
WLWPU-1	Mixing pump	02/12/04	M	P		Inspect drive belts and check for burning, fraying or cracking. Replace if required. Inspect drive pulleys for wear Check alignment of pulleys and belt tension. Realign and retention if required	as per work requested -
WLWPU-1	Mixing pump	19/01/05	M	F		STRIP PUMP AND REBUILD PUMP	overhauled pump, replace old mech seal
WLWPU-1	Mixing pump	26/12/04	P	F	Seized	Pumped tripped, please inspect.	freed up with stilsons
WLWPU-1	Mixing pump	17/01/05	M	F		Please change out pump 1 as the mech seal is leaking.	replaced old pump with spare
WLWPU-1	Mixing pump	09/02/05	M	F	Seal Leak	Pump 1 is leaking from around the shaft. Please inspect and repair	changed over pumps. laser aligned pulleys + tensioned belts to 350 nm. fitted new taper lock and gaskets
WLWPU-1	Mixing pump	11/02/05	M	F	Seal Leak	strip pump and investigate why pump leaked, rebuild pump.	stripped down. cleaned all mating surfaces. fitted new seals and o rings. rebuilt with new mech seal bench tested to 400kpa for 15 mins
WLWPU-1	Mixing pump	18/02/05	M	A		Please remove guard and check the drive pulleys have been replaced in correct position.	removed guard check pulleys ok.
WLWPU-1	Mixing pump	21/04/05	M	F	Seized	to please get pump 1running	as per work requested -

Table 17.7 – Subtotalling Annual Maintenance Costs by Equipment Item.

Asset No	Short Desc.	work_grp	cmpl_date	labour	mtl_cost	con_cost	workreq	corr_action
WLWBL-6	BOILER	FITTERS	23/06/04	$263	$2,563	$4,892	Strip down boiler for annual inspection Call in independent inspector to do internal inspections and running inspection Call in water treatment people to inspect boiler scale and adjust treatment	DONE ON SHUTDOWN
WLWBL-6	BOILER	ELECTRICIANS	04/05/04	$700	$859	$1,279	Some of the wiring at the back of the boiler at the bottom near the blowdown lines appear to be slightly burnt/melted	WIRING REPLACE IN ANACONDA CABLE
WLWBL-6	BOILER	FITTERS	14/05/04	$128	$0	$38	Can we please have blanks installed in the steam line to heater and drier steam line once the boiler is isolated, can these also be removed at the end of the shutdown.	As Per Work Requested
WLWBL-6	BOILER	ELECTRICIANS	27/10/04	$85	$0	$2,573	Lost power to LED display on the boiler	
WLWBL-6	BOILER	CIVILS-SUB	16/07/04	$0	$0	$3,480	Can we please have the blow down pipe work at the rear of the boiler lagged	INSULATION WAS PUT ON PIPEWORK AND METAL
WLWBL-6	BOILER	CIVIL TRADES	05/08/04	$170	$0	$102	The door on the boiler chemical dosing cabinet has broken off	
WLWBL-6	BOILER	FITTERS-SUB	12/08/04	$0	$53	$568	Please repair steam leak on boiler.	As Per Work Requested -
WLWBL-6	BOILER	CIVIL TRADES	12/08/04	$0	$0	$2,690	Can we please get the flu on the boiler pipes lagged	
WLWBL-6	BOILER	FITTERS	05/10/04	$85	$25	$681	Please have broke sight glasses changed out.	As Per Work Requested -
WLWBL-6	BOILER	ELECTRICIANS	19/10/04	$85	$0	$369	Require some electrical assistance to fix an electrical fault	Assist gas fitter to replace air proven and flame detector.
WLWBL-6	BOILER	FITTERS-SUB	15/01/05	$300	$0	$5,000	Strip down boiler for annual inspection Call in independent inspector to do internal inspections and running inspection Call in water treatment people to inspect boiler scale and adjust treatment	Boiler stripped and inspected. Repairs carried out to refractory inside the boiler. Running tests carried out and checked
WLWBL-6	BOILER	ELECTRICIANS	21/02/05	$85	$0	$0	There is currently no power to the boiler. Please inspect why.	RESET PWR AND OK
WLWBL-6 Total				**$1,901**	**$3,500**	**$21,672**		
WLWTK-6	FEED TANK	FITTERS	02/05/04	$250	$250	$0	PLEASE FIT SPADES TO TANK 6 x 2	As Per Work Requested
WLWTK-6	FEED TANK	FITTERS	03/05/04	$112	$186	$0	Can we please get hose connections installed to enable process condensate to go to the boiler feed water tank	done
WLWTK-6	FEED TANK	FITTERS	20/05/04	$128	$150	$0	TO REMOVE PIPEWORK BETWEEN PUMP AND TANK	
WLWTK-6	FEED TANK	FITTERS	18/04/05	$128	$92	$0	please put manway back on TK6 as per manual work order	As Per Work Requested -
WLWTK-6 Total				**$617**	**$658**	**$0**		

Table 17.8 – Investigation Results.

Category	Code	No of WO's	% of WO's	% Cost	Comments
During the 12-month time period there were 813 work orders raised in the plant.					
Job Type	Improve plant (I)	88	11	20	
The sort of work done on the work order.	Failure correction (F)	350	43	52	
	Assistance (A)	80	10	6	
	Blockage clearing (B)	73	9	7	
	Preventative (P)	220	27	15	These are PM's, condition monitoring and servicing.
WO Cause	Process Issue (P)	142	17.5	27	
The root cause of the work order being raised.	Design Issue (D)	89	11	21	
	Installation Issue (I)	20	2.5	2.5	
	Maintenance Issue (M)	382	47	40	
	Operating Need (O)	138	17	13	
	Statutory Need (S)	16	2	2.5	
	Else (E)	24	3	3	'Else' covers all WO's that did not fit into other codes.
Failure (F)	Process Issue (P)	84	24		
	Design Issue (D)	41	12		
	Installation Issue (I)	14	4		
	Maintenance Issue (M)	175	50		
	Operating Need (O)	6	2		
	Statutory Need (S)	4	1		
	Else (E)	23	7		

Analysis Interpretation

From the analysis, it appeared that:

1. True maintenance (repair work orders and PM's) was 60% of the work and 67% of cost.
2. Plant improvement work was 11% of the work and 20% of cost.
3. Operating support (Blockage cleans and assistance) was 19% of work and 13% of cost.

Of the repair work orders, it appears that:

4. The cause of 50% of the repairs was a real equipment problem.
5. The cause of 24% of the repairs was process characteristic related.
6. The cause of 16 % of the repairs was a design decision related (12%) or installation quality related (4%) factor.

Of the 813 work orders raised in the twelve months, 220 were for PM's to check for a condition problem with equipment or to do lubrication. There were 88 improvements and these would not repeat again. The remaining 505 were plant-related problems.

One major issue with this plant was its many random, unpredictable problems. The Time Series Table showed several equipment items with recurring equipment problems and others with recurring process problems. In the 12-month period covered by the study there were 105 repeating work orders from the 505-plant related problems. The recurring work was 20% of plant problems. The other 80% were totally random. You could choose to design-out the recurring problems. The random failures would be much more difficult to manage because they occurred without prediction.

You address random failures with precision maintenance and precision operation to prevent defect creating stress; by design selection of equipment that comfortably handles the operating stresses; with preventive maintenance to replace wearing parts, and condition monitoring to detect problems starting. This collection of strategies reduces the chance of having failures and addresses randomness by early detection to permit corrective action to be taken before failure.

A further strategy against random failure is to purposely select critical equipment and design-out the problems in the equipment before they cause trouble. This improves the equipment and designs in the reliability needed for high plant availability. Japanese engineers have a saying, "A new machine is in the worst condition it should ever be." They believe that it is the user's responsibility to modify and improve a machine to be highly reliable for its service. By looking for opportunity to improve your equipment's reliability you are following the advice of the world leaders in equipment reliability.

Because of the above analysis there were new strategies developed to reduce maintenance costs, new plans were created to address the process related problems and a chemical engineer was tasked to solve the process problems. The random failures were addressed by lifting preventive maintenance (PM) and condition monitoring (CM) inspections throughout the plant from 25% to 60% of all work orders. The costs of improvements and capital works, including the maintenance labour component, was capitalised. During the design stage of projects use of Failure Mode and Effects Analysis (FMEA) removed potential downtime causes. The work order analysis brought the organisation's maintenance problems to the surface for resolution.

Challenging Old Habits and Ways

If you are fortunate to have a fully integrated computerised maintenance management system then you can find every cent of value from the maintenance history. Even if a CMMS is not fully integrated with the other business systems, you can get huge value from what information there is. If you have a manual maintenance system there is still great value in those hand-written notes and scrawled list of used parts once they are in a spreadsheet! The time spent analysing work order history is an investment in your company's future. You are on the trail to discover the causes of your problems and to see if there are ways to solve them. That has to be important to the future success of your organisation! If the solutions to the problems are minor costs and not difficult to implement then get on and make the changes to fix them.

The engineering problems you discover are the easy ones to fix. They require some design effort and some money spent on them. They will be easily financed because the DAFT Costs prove how horribly expensive they are. The system-induced and ignorance related problems will be magnitudes harder to solve. Those problems are, unfortunately, the most common cause of failure in a business. The systematic and lack-of-knowledge problems are the ones you must solve if you want a strong, vibrant, healthy organisation with a long-term future. Talk to the people affected by what you discover. Show them the consequences of the problems on the organisation and its business. Immediately enlist their help in solving the easy issues by asking them what they suggest is the best way to resolve them. Do not argue with them or question their suggestions, after all, they know their jobs better than you do. They are the 'local experts'. Simply support them in their efforts to make the necessary changes. If they have problems give them the opportunity to come back and talk to you about them. That is when you give them your advice, but not until they show you that they need it.

Use the 'Change To Win' team approach of involving people in making improvements. The workbook for the 'Change To Win' 100-day program is included in the CD accompanying this book. It gets people together working as teams and helps them to become knowledgeable in a problem so they can fix it properly themselves.

18. Reliability Growth

Quite literally, you can choose the failure rate you want for your plant and equipment and then put into place the practices and methods that naturally deliver it.

Failure Patterns and Failure Modes

Equipment failure follows one of the six probability patterns in Figure 18.1, made famous by the 1978 Nolan and Heap study into aircraft equipment failures [73]. Evidence from airline industry maintenance in the 1960s and 70s indicated that together failure patterns D, E and F represented 89% of aircraft equipment failures. With pattern F, showing infant mortality failure, alone representing 68%. Other airlines and the USA Navy conducted similar studies and confirmed the patterns. Though the proportions varied with different industries, patterns D, E and F dominated. The curves highlight that once most equipment are through the early-life period, failure is not age related but is 'random' and can happen anytime. This does not mean there is no reason for a failure, there definitely is, but when the event will happen is uncertain. Nolan and Heap questioned the practice of doing regular overhauls, since if most equipment failures (89%) had nothing to do with the age of the equipment, why were parts replaced on a time basis. You could be throwing away a perfectly good part still suitable for many hours of service, and introduce early-life failure from human error.

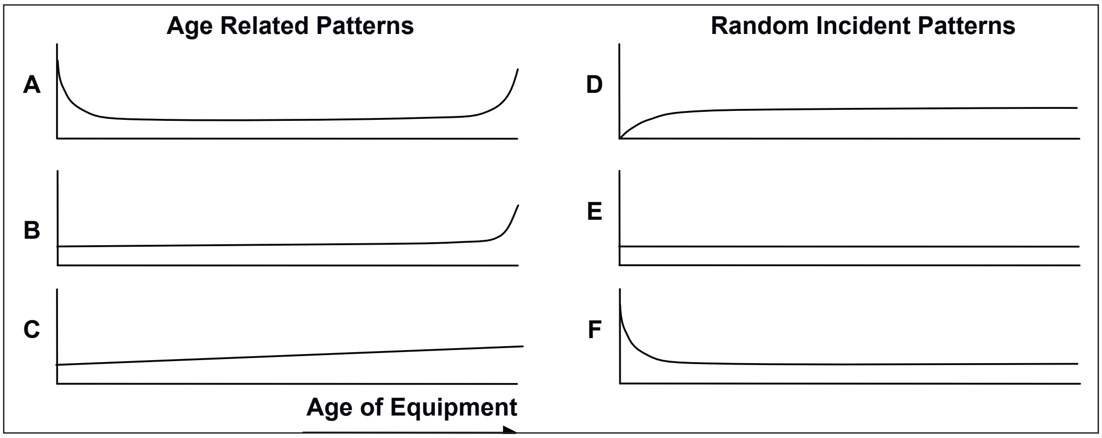

Figure 18.1 – Six Failure Patterns for Parts
(only applies to 'parts', not overhauled assemblies).

The recognition that few equipment failures are age related allowed development of a new methodology in the airline industry called Reliability Centred Maintenance (RCM), where maintenance strategies matched the operating risk caused by failure. Unless the consequence of failure was so severe that it could not be allowed to occur, RCM required proof of failure starting before maintenance was conducted. If failure was unacceptable, or expensive, then equipment was redesigned to remove failure modes. Alternately, age-based refurbishment and fixed time replacement was demanded after set hours of operation and well before parts could fail. All other equipment required condition monitoring to find evidence that maintenance was necessary. RCM allowed preventive maintenance to be replaced by on-condition maintenance.

[73] Nolan, Stanley F, Heap, Howard F., 'Reliability Centred Maintenance', Dolby Access Press, 1978.

There is some uncertainty in the veracity of the original analysis used by Nolan and Heap [74]. The 1970s actuarial analysis of failure data incorrectly mixes together parts replacement and complete equipment renewal. Replacing selected parts still leaves those parts not replaced untouched. The old parts contain accumulated stresses and are no longer as strong as new. The weakened older parts are at greater chance of failure from stress incidents than the new, stronger parts. It is not equal to compare the failure rate of equipment repaired by replacing selected parts with equipment fully overhauled and fitted throughout with new parts. This misunderstanding raises questions over the true causes of equipment failure and the proportions of each failure curve.

Because RCM is limited to using maintenance practices to reduce equipment operating risk it is not used in Plant and Equipment Wellness. Equipment risk reduction in Plant and Equipment Wellness is driven by economic considerations of failures. RCM reserves cost analysis only for extreme financial risks. This leads to the same problem as RCFA (Root Cause Failure Analysis) suffers, which is that it is reserved for removing catastrophic failures and so companies continue having catastrophic failures. By doing RCM without knowing the cost of an event before selecting mitigation there is insufficient understanding on which to make good economic risk-based decisions. The restrictions on financial analysis of failure in RCM means a business is using a process that cannot deliver what it wants. The maintenance crew ends up being busy but no one is sure it is actually to the company's benefit.

Plant Wellness uses standard risk management methodology and demands cost be considered for every risk situation. The body of knowledge on risk analysis and management is well accepted, well documented and completely appropriate in industrial situations to rate risk and develop mitigation practices. It is already applied in identifying Equipment Criticality and is a methodology well known to maintenance and project groups. If there is risk and safety management expertise existing in a business those people have the knowledge and skills to be a resource immediately available to the maintenance group for risk analysis.

Plant Wellness uses computers to do DAFT Cost calculations to permit easy manipulation of large amounts of financial data and quick 'what-if' scenario analysis not possible with RCM. Instead of tying up lots of people in a team doing RCM, risk analysis and costing uses one person, with the team being saved for review of the analysis and risk mitigation selection. Risk control in Plant Wellness is required throughout the life cycle and applied by everyone. It is not limited to maintenance activity only.

Reducing Equipment Parts Failure

Understanding the cause and effect relationships of equipment and operational problems is an essential part of an effective maintenance program. The parts in a piece of equipment can only fail in a limited number of ways or 'failure modes'. A parts-hardware level FMEA finds the likely failure modes and lets people decide what to do. If failures can be detected after initiation by physical inspection, or with condition monitoring, then the problem is corrected before failure. When the DAFT Cost consequences of a failure are unimportant the parts can be let run to destruction and then replaced. Where the consequence of failure is important actions are put into place to prevent the failure. These include defect eliminating precision practices, regular overhauls of parts with age-based failure characteristics, total replace of equipment when key parts approach end-of-life and equipment redesign to remove failure modes.

The purpose of maintenance is to deliver improving equipment reliability. We do that by

74 Sherwin, David, 'A Critical Analysis of Reliability Centred Maintenance as a Management Tool', Australian Asset Management Council ICOMS 2000 Presentation.

continually removing the risks that cause equipment parts to fail. Parts failure curves are malleable; they can be changed by the selection of engineering, operating and maintenance policies and practices. Recall the story of the diesel engines used on a ship that had three times less maintenance cost than identical engines used in a locomotive. Because of the policy decision to de-rate engine duty to 90% of nameplate capacity they saved much operating downtime and maintenance cost. The evidence of successful reliability improvement shows up as falling rates of parts failure and greater operating life of equipment. Figure 18.2 shows the changed failure rate of equipment parts by choice of appropriate policies and use of the required methods.

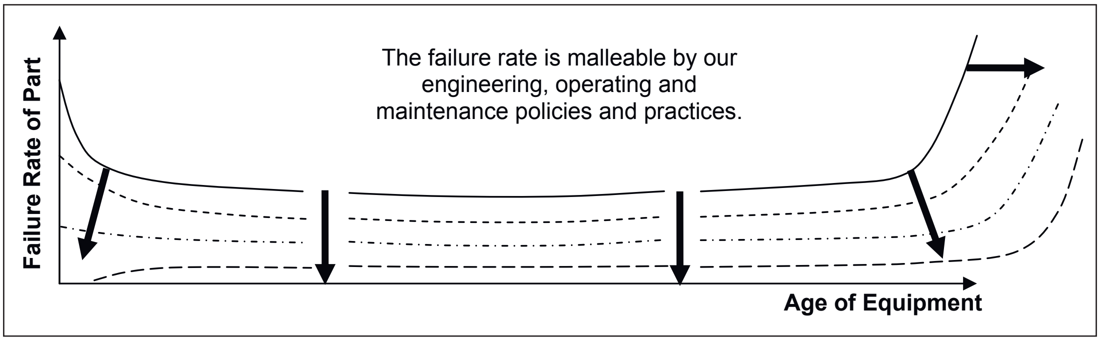

Figure 18.2 – The Rate of Failure is Malleable by Choice of Policies and Practices.

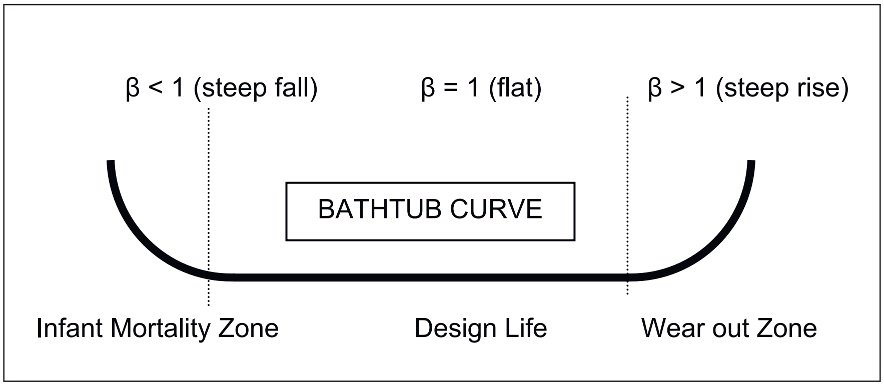

Figure 18.3 – Weibull Wear-out Life Curve.

Weibull Analysis [75]

Waloddi Weibull identified the Weibull distribution in 1937 while seeking a formula for the failure rate of welds. It is now one of the most commonly used methods for fitting equipment life data and used extensively in the aviation industry to optimise maintenance intervention and select maintenance strategy. The essence of Weibull's work was to discover he could represent the Bathtub Curve of Figure 18.3 using mathematical formula. His equation could mimic the behaviour of a combination of other statistical distributions, which were each of limited use, by changing its shape. It could represent all the zones of the bathtub curve by using the three Weibull parameters – beta β (shape parameter), eta η (life) and gamma γ (start location). Note that the 'beta' used in Weibull Analysis has a different meaning to the

[75] Note: Some of the content for the topic was provided by Michael Drew, Director, ARMS Reliability Engineers, Australia.

'beta' of Crow-AMSAA plots. The Weibull shape parameters provides the owners, users and maintainers of equipment with a tool to use the failure history of their operating plant and predict the behaviour of components and items of equipment replaced as complete units. The analysis directs selection of effective equipment maintenance strategies and design-out efforts to reduce parts failure.

$\beta < 1$ implies infant mortality. Electronic and mechanical components often have high failure rates initially. Some components are purposely 'burnt in' prior to use, while others require careful commissioning after installation. The presence of infant mortality indicates poor training, lack of procedures and poor quality control.

$\beta = 1$ implies random failures. These failures are independent of time and an old part has the same chance of failure as a new part. Maintenance overhauls are not appropriate for random failures. Condition monitoring and inspection are strategies used to detect the onset of failure and then reduce the consequences of failure. This zone is affected by random incidents and accidents. It reflects poor operating procedures, poor risk management and poor materials selection at design.

$1< \beta <4$ implies early wear out. You would not expect this type of failure within the design life. Failure mechanisms such as corrosion, erosion, low cycle fatigue and bearing failures fall in this range. Maintenance often involves a periodic rework or life extension task. The shape can be altered by better materials selection, by degradation management and by good control of operating practices.

$\beta > 4$ are wear-out or end of life failures. They should not appear in the design life. Age related failures include stress corrosion cracking, creep, high cycle fatigue, and erosion. Appropriate maintenance is often the renewal of the item with new.

An ideal profile for equipment is to have a negligible failure probability throughout its operating life followed by a steep beta that predicts the replacement age. Figure 18.4 shows such a profile.

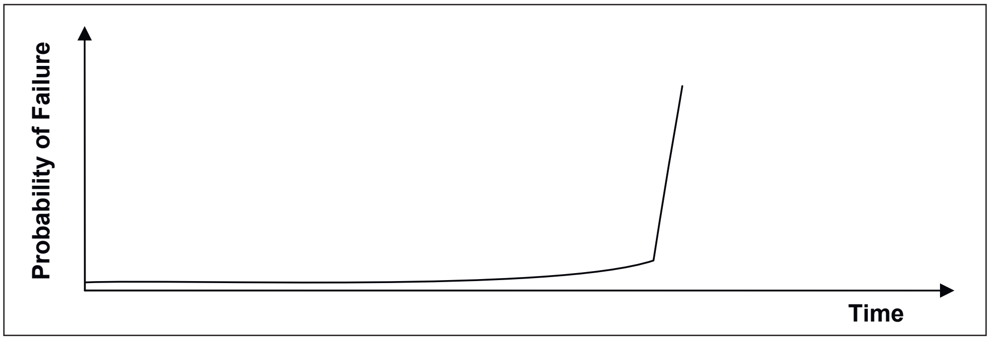

Figure 18.4 – Ideal Failure Profile for Parts.

A drawback of Weibull analysis is the implied assumption that the future is the same as the past. As soon as design, maintenance or operating policies and practices change the prior failure history is unrepresentative of the future. An analysis using the old data to predict the future would be wrong. Weibull Analysis requires complete and accurate failure data over a period of stable practices. The analyst requires thorough understanding of the effects of past and current maintenance and operating policies and practices.

Weibull Analysis is used on failures of the same mode. This is most important. A Weibull plot only applies to one failure mode of an item. It is a false analysis to predict the life of a part that fails for several reasons (e.g. a bearing can have several failure modes – overload, distortion, run short of lubricant, run with water in the lubricant, etc), or for a complex machine made of many parts. You must plot each part's failure modes separately [76]. Note that in Weibull Analysis a 'part' is defined as a replaceable item. Provided the complete assembly or equipment is replaced at every failure Weibull Analysis can be used. For example, if a mechanical seal, or a drive coupling, or gearbox fails and each is always replaced with a complete assembly, then the mechanical seal, coupling and gearbox are seen as a 'part'. If however the assembly is stripped and the failed parts replaced, and the repaired assembly is then reinstalled, it would not be suitable for Weibull Analysis. A part replaced in the assembly would qualify for analysis, but not the entire rebuilt assembly.

Beware that repeated overhauls of complex equipment result in ever decreasing times between failures after each overhaul. When old parts are reused from one overhaul to the next, the equipment has increasing chance that it will fail sooner than last time. The reused parts are already fatigued and distorted. When used again they fail sooner because prior service stresses reduce their remaining usable life. Having already had a life, they are perhaps close to the end. It is good strategy to identify when equipment parts have accumulated too many service hours of use, or too many overstress cycles, and replace the entire equipment with new [77].

Weibull Analysis predicts probabilistic safe intervals for operation. It helps in selecting the optimum maintenance type and interval so the cost of spares and downtime are minimised for maximum reliability. With sufficient failure data points Weibull Analysis can advise if Preventive and Predictive Maintenance, or re-design, be investigated to improve a component's reliability. With Weibull Analysis you can compare the cost and estimated effectiveness of your options. You can determine if re-design, or extra quality precautions in assembly, or whether to initiate measures to reduce operational loads and stresses, are the best choice for the business. It applies to deciding warranty periods, shutdown intervals and setting maintenance and inspection intervals. Accurate Weibull Analysis needs trustworthy parts failure data with clear failure modes. With a sophisticated CMMS in use, the collection of failure mode data is more reliable and data analysis can be done electronically.

Many organisations have kept records of failures but not used the data in any useful way. Site failure data is the best source of reliability information available. It is highly relevant and site people can relate their own experience to it. By using your maintenance and parts history you can make failure forecasts, model the benefits of alternative strategies, or analyse the reliability of current systems and their capacity to meet operating needs.

Life Cycle Simulation

Once the Weibull parameters that best fit failure mode behaviours are available they can be used to simulate performance over extended periods. If you have a mathematical model of a part's past you can use the same model to predict its future. Provided the part is treated the same in future as it was in the past, the model is believable. Modern simulation packages involve a Monte Carlo simulation engine that generates random effects in accordance with the historic Weibull parameters over a specified system lifetime. It attempts to mimic what will happen to the part in service if its future were to remain the same as its past. Used in conjunction with FMECA principles, the process of selecting maintenance and inspection intervals becomes a process of playing 'what if' with the Weibull software by comparing the probabilistic effects of different reliability strategies. You then know how to adjust your maintenance to bring the most benefits to the business.

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

77 Gurgenci, Hal., Zhihqiang, Guan, 'Mobile Plant Maintenance and the Duty Metre Concept', Journal of Quality in Maintenance Engineering, Vol 7, No4, 2001.

Reliability Growth Cause Analysis (RGCA)

Improved reliability has a cause. Just like a failure has a cause, so too is there a cause for improved reliability. You can wait for a failure to happen and then learn from the experience and change your processes to prevent it. That is root cause failure analysis. But it is not proactive behaviour. Such an approach quickly buries you in fire-fighting. It helps you fix a few terrible failures, but not the tens of thousands of defects that are waiting to create the next lot of disasters. Permanent reliability growth requires proactive methodologies that identify all potential problems and stops them from starting. This is what is done in high reliability operations – they never allow defects to begin.

The process maps of your business processes, the workflow diagrams of your operating procedures and the bills of materials for your equipment are the foundation documents for improving equipment reliability. They are used respectively to control the business processes, to control human error and to address limitations in materials of construction and parts' health practices.

Reliability Growth Cause Analysis (RGCA) uses team brainstorming to find ways to grow reliability in a business process or equipment part. It looks for what can be done to intentionally reduce stress and remove risk from a situation. A process map is drawn of the process, or work tasks, or for a machine. The map is used to identify every possible way to prevent failure and eliminate defects throughout the life cycle. Box by box of a process, or part number by part number of a bill of materials, every identifiable way to remove and prevent stress, or to improve the working environment, or to eliminate risk to reliability is identified. Details of the causes of reliability are listed in a spreadsheet, along with the required information about failure and its prevention. Table 18.1 shows the requirements. Together the team identify the strategies, practices and skills needed in design, manufacturing, procurement, construction, operations, and maintenance to deliver lifetime reliability. A plan is developed to introduce them, including all necessary documents, training and skills development.

Table 18.1 – Reliability Growth Cause Analysis Requirements.

Failure Description: ______________________________ **Failure Cause: __________________________________**
• Frequency of Cause:
• Time to Repair:
• DAFT Cost:
• Causes of Stress/Overload:
• Causes of Fatigue/Degradation:
• Current Risk Matrix Rating:
• Controls to Prevent Cause:
• Est. failures prevented after risk controls in use (/yr):
• New Risk Matrix Rating:
• DAFT Cost savings from higher reliability:

The RGCA method adopts the same strategy for reliability growth as the world-class leaders in industrial safety use for workplace safety improvement. They proactively improve safety by identifying safety risks and installing appropriate protection and improvements against harm before incidents happen. They don't let hazards that can become accidents even start. RGCA assumes that failures will happen to equipment parts from defects created in engineering, manufacturing, operations, maintenance, installation and procurement processes unless they are intentionally prevented. It requires recognising what can cause risk in all stages of a part's life-cycle and make necessary improvements to prevent every cause starting. Reliability grows by using the right practices and processes that prevent defects and proactively promote health and wellness. RGCA requires you to identify ways that will drive improvement and not simply prevent failure. The aim is to never allow a process step or part to fail so that reliability is maximised. The level of business risk determines which reliability growth improvements will be used and then drives their rapid introduction.

An example of the RGCA methodology is used to maximise the reliability of the inner race of the bearing shown in Figure 18.5. The process map of the shaft and bearing arrangement in Figure 18.6 confirms the configuration is a series arrangement. Hence it is an at-risk assembly and the electric motor would stop should any item in the series fail.

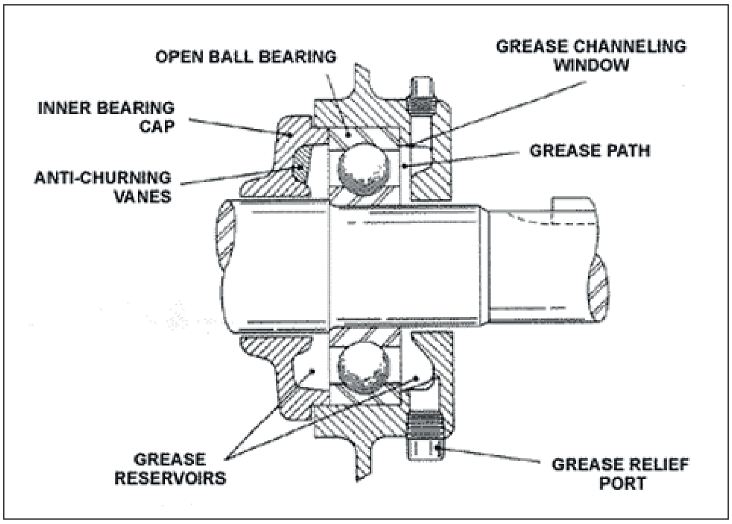

Figure 18.5 – AC Electric Motor Bearing Arrangement.

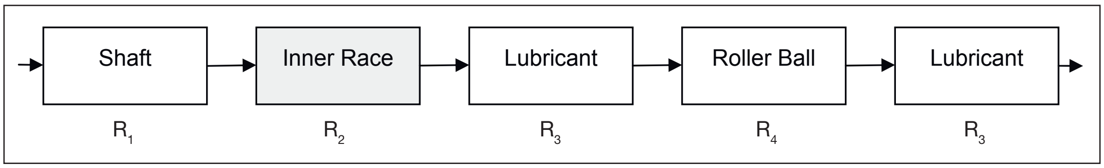

Figure 18.6 – Process Flow Map for Roller Bearing on Shaft.

First, a list of known and possible inner race failures is brainstormed by the analysis team. Known inner race failures include a cracked race, a scoured and scratched race, a brinelled and indented race, a loose fitting race, a race suffering electrically arcing, and so on until the team has exhausted all failure modes known to its members. Possible failure modes are then imagined. These include a cracked race intentionally installed and a cracked race unknowingly installed. The next step is to ask of each failure mode how its cause can arise – how can the inner race be cracked? A cracked race can occur from excessive interference fit on the shaft, or a huge impact load, or the shaft is oval and the round race is forced out-of-shape, or a solid piece of material is trapped between the race and shaft during the fitting, or the shaft is heavily burred and the race is forced over the burr and is damaged in the installation process.

Table 18.2 – Example of Reliability Growth Cause Analysis on Inner Race of a Roller Bearing.

Failure Description: Cracked inner roller bearing race		
	Failure Cause 1: Excessive interference fit	**Failure Cause 2:** Impact to race
Frequency of Cause:	Early Life – 1 per year	Random – 3 per year
Time to Repair:	5 hours	10 hours
DAFT Cost:	$20,000	$25,000
Causes of Stress/Overload:	• Large shaft • Small bearing race bore	• Abuse when fitting • Start-up with equipment fully loaded
Causes of Fatigue/Degradation:	Not applicable	• Misaligned shafts • Loose race moving on shaft
Current Risk Matrix Rating:	Medium	Medium
Controls to Prevent Cause:	• Update all bearing fitting procedures to measure shaft and bore and confirm correct interference fit at operating temperature and train people annually • Update all machine procurement contracts include quality check of shaft diameters before acceptance of machine for delivery • Update all bearing procurement contracts to include random inspections of tolerances • Update all design and drawing standards to include proof-check of shaft measurements and tolerances on drawings suit operating conditions once bearing is selected	• Update all bearing fitting procedures to include using only approved tools and equipment and train people annually. Purchase necessary equipment, schedule necessary maintenance for equipment • Change operating procedures to remove load from equipment prior restart and train people annually (Alternative: Soft start with ramp-up control if capital available) • Align shafts to procedure and train people annually • Update bearing fitting procedures to measure shaft and bore and confirm correct interference fit at operating temperature and train people annually
Est. failures prevented after risk controls in use (/yr):	All future failures	80% of future failures
New Risk Matrix Rating:	Low	Low
DAFT Cost savings from higher reliability:	$20,000 per year	$60,000 per year

For the first cause noted of a cracked inner race – excessive interference fit – the team asks, "How is excessive shaft interference prevented?" This problem is one of incorrect tolerances between race and shaft. It is usually a manufacturing error of the shaft or the race. The team is now required to develop proactive measures to ensure a race is never fitted to an incorrectly made shaft, or an incorrectly made race is never fitted to a good shaft. One prevention is to micrometer the shaft and the race and check the fit matches the bearing manufacturer's requirements for the model of bearing. Additional prevention is to confirm the model of bearing is correct for the service duty and operating temperatures. These checks become a procedural requirement written into the applicable ACE 3T procedures. But the team is charged with finding all cause of reliability and much more can be done earlier in the life cycle to prevent this failure. These additional early life cycle preventive measures are listed in Table 18.2.

The team then continues with the next cause of how an inner race can be cracked – heavy impact – and develops preventive actions (heavy impacts can occur when a race is fitted to a shaft with hammer blows or overloaded in a press, or a loose race on the shaft rattles from side to side, or a badly aligned shaft causes the race to be cyclically loaded, or it suffers a huge start-up overload). The process continues for a shaft that is oval, for a solid piece of material trapped between race and shaft during the fitting, for a heavily burred shaft, and so on. With each preventive measure put into place, and made standard practice through using ACE 3T procedures and workforce training, each part's reliability grows.

Every RGCA performed applies to every similar situation, and the learning from one analysis is transferred to every other similar situation by updating all other applicable procedures. In this way RGCA applies Series Reliability Property 3 and rapidly improves every other like circumstance.

Measuring Reliability Growth

If your reliability improvement efforts are working the evidence will be a reduction in the number of equipment failures. There are several ways to detect the change.

Time Series Plots

By measuring the time between failures you can see if the period is increasing (reliability is improving), decreasing (reliability is worsening) or unchanged. Figure 18.7 shows how improving equipment reliability would look on a 'time between failures' plot for an item of equipment.

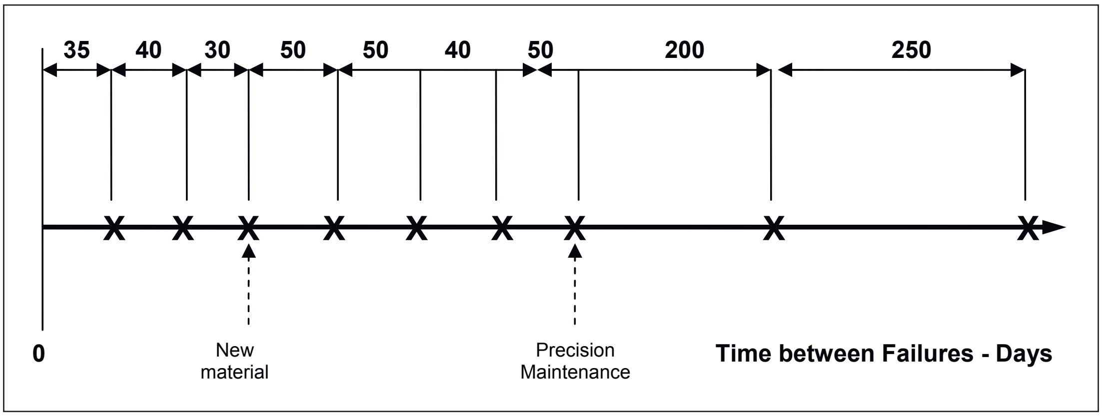

Figure 18.7 – Time Series Plot Showing Increasing Time between Failures for a Component.

The 'X' on the timeline represents the failure of a part or assembly that causes the equipment to fail. There may be a variety of parts in an item of equipment that can fail and a variety of ways to fail each part. The time series above simply reflects when the equipment failed. If correct information on each failure mode was available, a time series by failure mode could be developed. The time series plot clearly shows that from a history of frequent failures every 30 to 40 days, the days between failures have increased – the part is lasting longer and longer. The time series plot represents reliability growth and the effect of changes on the health and wellness of the machine.

The mean time between failures (MTBF) in the early life period was:

$$\text{MTBF} = \frac{35 + 40 + 35}{3} = 37 \text{ days}$$

Following the material change, it became:

$$\text{MTBF} = \frac{50 + 50 + 40 + 50}{4} = 47 \text{ days}$$

After the introduction of Precision Maintenance, it became:

$$\text{MTBF} = \frac{200 + 250}{2} = 225 \text{ days}$$

Duane/Crow-AMSAA Plots

Another way to see reliability growth is by plotting the observed number of cumulative failures against cumulative time on logarithmic paper. Such a diagram is known as a Duane reliability growth plot and applies for a piece of equipment, a complete production process and even to an organisation. The development of log-log reliability growth plots can be traced back to the 1930s investigations of the learning curve for building airplanes [78]. It was developed into a graphical method in the 1960s by James Duane while working at General Electric for use in predicting reliability improvements of new product developments. In the 1970s a mathematical derivation was developed by Larry Crow while in the employ of US Army Material Systems Analysis Activity (AMSAA). The measurement of reliability growth reflects changes in system reliability caused by changed efforts to affect reliability.

The method is now used in industry as a historic reliability key performance indicator, as well as a means to predict the future impact of reliability improvement initiatives. The technique is purely empirical, but has been a very good approximation when applied to complete machines suffering multiple failure modes [79]. Duane/Crow-AMSAA plots are power laws that measure failure rates. They imply a relationship between the failure of equipment and the chance of failure it carries.

A Duane plot starts by creating a table like Table 18.3, which in this case lists the failure dates for the time series plot of Figure 18.7 and the cumulative days between failures. On a computerised log-log plot, like that in Figure 18.8, or in 1:1 scale on a sheet of log-log paper, like Figure 18.9, a graph is drawn of the cumulative days verses the cumulative failures.

Table 18.3 – Reliability Growth Cumulative Days.

Failure No	Failure Date	Cumulative Time in Days	Comments
0	January 25th		New equipment installed
1	March 1st	35	
2	April 9th	75	
3	May 9th	105	New material selected
4	June 30th	155	
5	August 21st	205	
6	October 5th	245	
7	November 26th	295	Precision Maintenance introduced
8	July 1st	495	
9	March 26th	745	

In the log-log plot of Figure 18.8 there are three identifiable regions – one reflecting the period of the first three failures, another following the material change and the third following the introduction of precision maintenance. The change of material made a small improvement. You can tell that from the changed slope of the line in that portion of the graph. The slope after the material change is shallower than before the change. The fact the line is straight implies that the failure rate was relatively constant and the small reduction in slope indicates there was slight

78 Comerford, Nigel, 'Crow/AMSAA Reliability Growth Plots and there use in Interpreting Meridian Energy Ltd's, Main Unit Failure Data', Areva T&D, New Zealand, 2005.

79 Sherwin, David, Retired Professor of Maintenance and Reliability, 'Introduction to the Methods of Reliability Engineering with particular emphasis to Engineering Asset Management and Maintenance' presentation, 2007.

improvement on its earlier life. You can also confirm those observations on the time series plot of Figure 18.7 where the change of material improved the Mean Time Between Failure from 37 days to 47 days. The big improvement came with introduction of precision maintenance when MTBF jumped to 225 days. The slope in Figure 18.8 shows this great improvement.

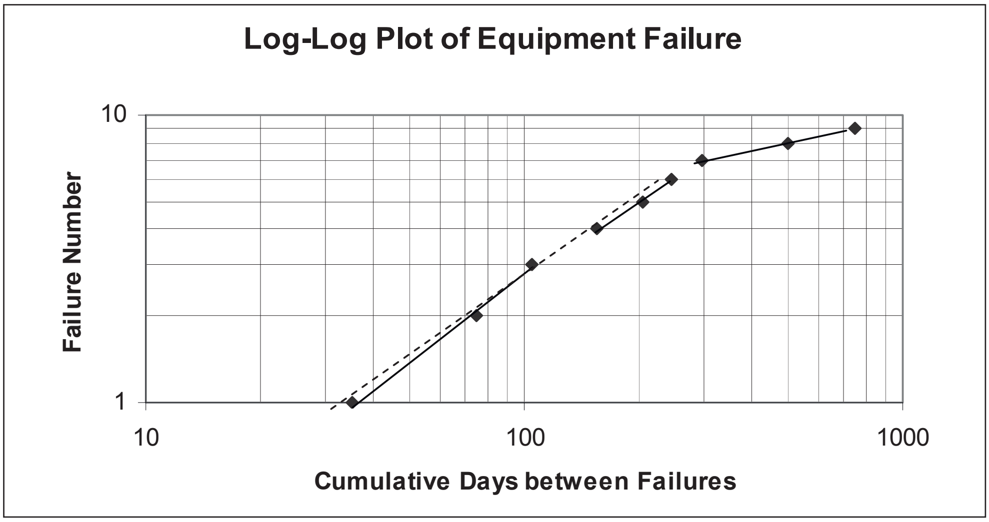

Figure 18.8 – Duane Log-Log Plot of Equipment Reliability.

Notice the triangles drawn on Figure 18.9 have the same slope as the lines. Because the graphical log-log plot is 1:1, you can measure the X and Y lengths with a ruler and calculate the slopes. The slopes tell a lot about what is happening with the equipment. The slope is called the Beta Value – 'β' (not to be confused with the beta used in Weibull Analysis; the two have very different meanings). The Beta is a reliability trend indicator.

- Beta < 1, Reliability Improving
- Beta ~ 1, Reliability Static
- Beta > 1, Reliability Deteriorating

In Figure 18.9, you can see that the beta for the early failures was indicating a steady reliability trend. After the material change, the reliability was better. With the introduction of precision maintenance the reliability trend improved massively.

Software for Crow-AMSAA investigation and reliability improvement analysis is commercially available and provides useful management indicators when sufficient data points be available.

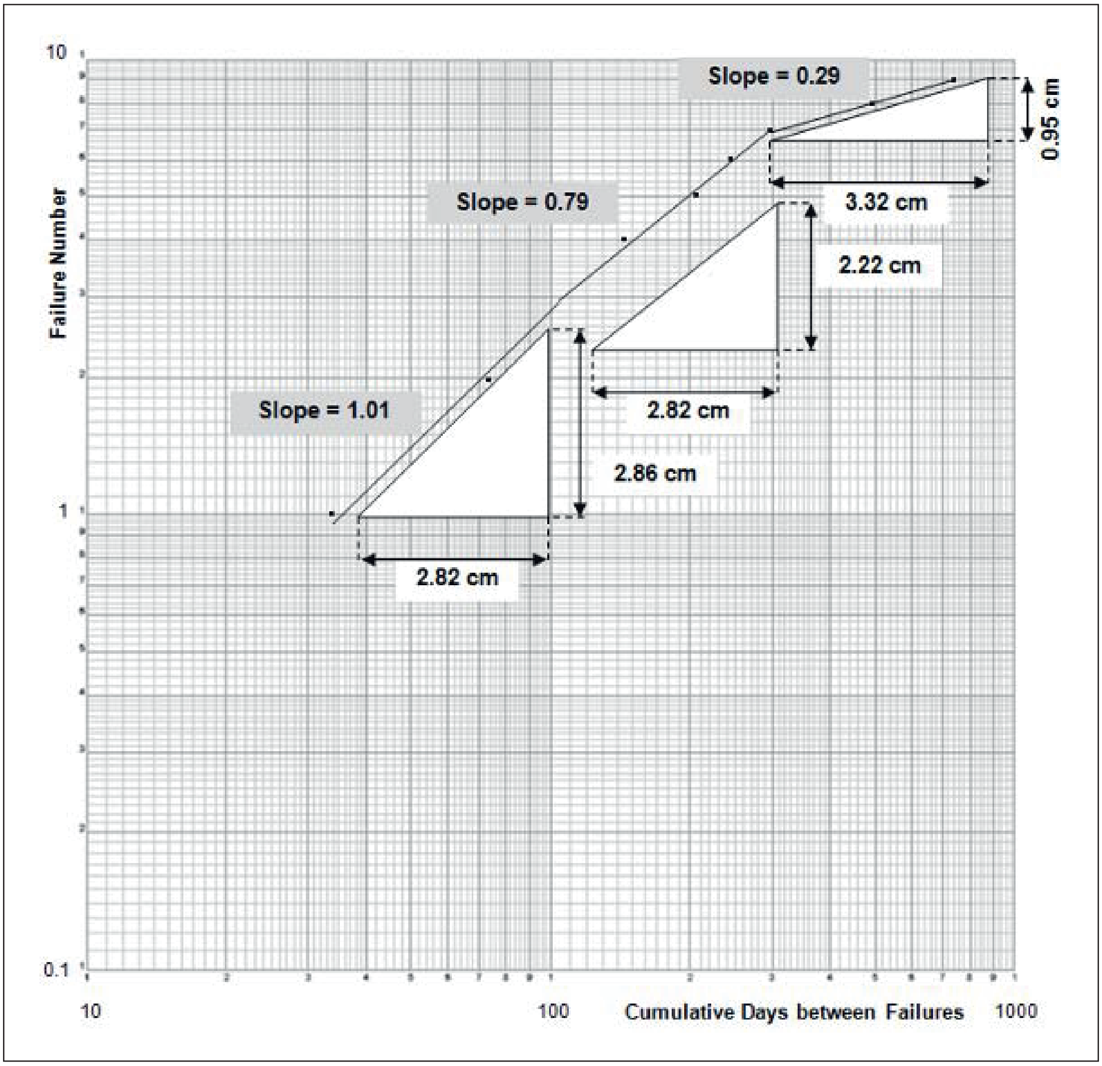

Figure 18.9 – 1:1 Scale Log-Log Paper Plot of Equipment Reliability.