Chapter 21
Reliability, Availability, and Maintainability

Abstract To introduce key elements of reliability, availability, and maintainability (RAM) from an asset management perspective. *Outcomes* After reading this chapter you will be aware of the need to specify and check for RAM requirements for asset acquisitions and developments. You will learn about how RAM are measured, and about the factors that lead to successful management of assets in regard to RAM considerations. You will be aware of a number of specific techniques which assist with these tasks.

21.1 Introduction

The topics of Reliability, Availability, and Maintainability (RAM) are important areas of competence for asset managers.[1] As these fields have significant technical depth, a range of levels of expertise can be expected within an asset management group. In a technically specialized organization, there may be a dedicated section specializing in Reliability Engineering and related topics.

In this chapter, the main concepts and techniques will be introduced but they will not be treated in a numerical way. This material is particularly applicable for more technically sophisticated assets.

21.2 Reliability

Reliability is the ability of an item to perform a required function under stated conditions for a specified period of time.[2] Reliability is important because failures reduce the effectiveness of service and undermine the organizational objectives which the

[1] ISO 55002 Clause 6.2.1.3 Asset management objectives. "… issues … addressed include … asset system availability … reliability … condition … life expectancy …".

[2] Dictionary of Military and Associated Terms. US Department of Defense 2005.

N.A.J. Hastings, *Physical Asset Management*,
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assets are intended to support. Failures may also have safety and environmental implications. The cost of failure is generally disproportionately high when considered against the costs of sound maintenance, repair, and replacement policies.

21.3 Specification and Testing[3]

The specification of an asset should include consideration of RAM. At the acquisition planning stage we carry out tests of prospective equipment to check whether the RAM specifications are met. Performance and RAM characteristics must be also checked prior to specific equipment acceptance. Otherwise, the equipment may fail to deliver a reasonable level of service.

The specifications for RAM, will be based on technical input and judgement from knowledge of the type of equipment concerned and the service conditions and requirements involved. The tests will involve operating the equipment for a trial period during which equipment performance, faults, failures, and maintenance activities are recorded and analyzed. The results should then be compared with the required specifications, and may be used to compare competing equipment. Faults may be reduced and performance improved as trials proceed, but finally a judgement is made as to whether the equipment is satisfactory in relation to the specifications, and meets criteria for quality and safety.

Trials also provide information regarding logistic support requirements including maintenance and replacement policies and spare parts planning. It is important to make data-supported decisions on all these topics wherever possible.

21.3.1 Mean Time Between Failures

The most commonly used measure of reliability is the Mean Time Between Failures or MTBF. This is defined as follows:

Mean Time Between Failures (*MTBF*) is the average time for which an equipment operates between failures occurring.

21.3.2 Failure Rate

The *failure rate* is the number of failures per unit of operating time.

[3] ISO 55001 Clause 10.2 Preventive action: "The organization shall establish processes to … identify potential failures …".

21.3.3 Failure

A *failure* is a deterioration of an item such that it is no longer able to perform its required function. However, some failures may have only a minor impact on equipment operation. Care must be taken in deciding what constitutes a failure in any analysis or in any form of reliability trial.

21.4 Design for Reliability[4]

The design of equipment should reflect the level of reliability required by the application specification. At the design phase, techniques such as Failure Mode and Effects Analysis (FMEA) are applied to assess how an item may fail and to subsequently reduce the risk of failure. Besides the design of the equipment itself, the reliability of a system is influenced by the degree of *redundancy*. In systems where high reliability is required, this is often achieved by having components, assemblies, or units working in parallel, or on standby, so that if one item fails the system remains operational.

21.5 Managing the Reliability of In-service Assets

Beyond the initial acquisition stage, where reliability will depend largely on design factors, reliability should be managed throughout the life of an asset. Many techniques have been devised to assist in this process and some of these are outlined in this section. Figure 21.1 gives a flowchart relating to the management and improvement of reliability. The techniques named will be considered in this chapter. Full details are given in books dedicated to reliability, such as O'Connor.[5]

21.5.1 Operator Records and Incident Reports

Operator logs or records form a useful source of information about equipment performance and condition. The frequency and extent of delays, losses, or faults can be determined directly and in a timely manner from these logs. Following up

[4] Stapelberg, R.F., Handbook of Reliability, Availability, Maintainability and Safety in Engineering Design. Springer 2009.

[5] O'Connor, Patrick D. T, "Practical Reliability Engineering", 4th ed., John Wiley & Sons, 2002.

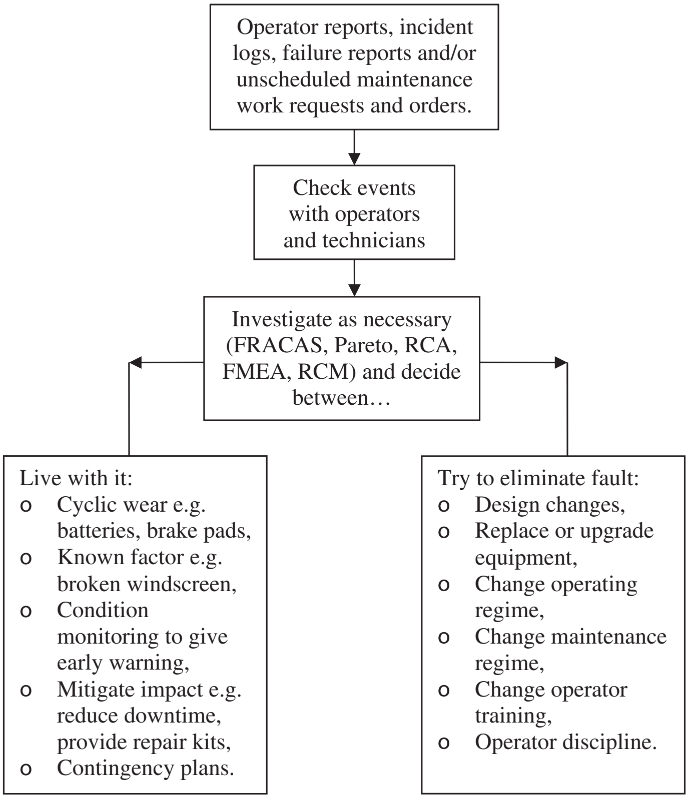

Fig. 21.1 In-service reliability management

on the data from operator logs can lead to the determination of causes of problems and to action to eliminate or mitigate problems. Data from work requests and work orders are also valuable and form the normal basis for failure investigation, but operator logs are relatively neglected as a source of useful information for reliability improvement.

21.5.2 Toolbox Meetings

A toolbox meeting is a meeting of maintenance personnel with supervisors and planners, typically held weekly as part of the maintenance planning and scheduling process. Feedback from maintainers forms a valuable source of information relating to in-service asset reliability.

21.5.3 Management Reaction

The key step here is for management to listen to the feedback and to take corresponding action where warranted. The reporting and management of incidents forms a basis for managing the performance and reliability of assets. There is a saying that 30 incidents become one accident and 30 accidents become one fatal accident. The causes of losses and incidents should be investigated and steps taken to prevent future occurrence and to mitigate the consequences.

Some specific pointers are as follows:

- Staff to be given time, encouragement, and processes to record incidents, errors, mistakes, faults, problems, defects, and failures;
- Retaining defective or broken parts and materials, e.g., in a tray or bucket, taking photos including close-ups, making written records, refer FRACAS and Root cause Analysis (RCA) techniques;
- Problems to be resolved or referred upward. Meetings to be arranged with shop floor personnel to allow time for reporting and discussion;
- Technical support to be available to assess incidents, provide feedback and take suitable action as appropriate;
- Do not just fix it, improve it so that it does not fail again;
- Bad news to be passed on as first priority;
- Systematically retain plant knowledge;
- Systematically disseminate plant knowledge;
- Minority opinions to be aired—suffer fools gladly, they may be right;
- Innovation and automation to be treated with caution.

21.6 Failure Patterns and Causes

Reliability analysis involves an understanding of patterns and causes which commonly arise in relation to equipment failures. There are three common failure rate patterns:

- Burn-in or early life or infant mortality failures;
- Random failures, the term random meaning "not age related" in this context;
- Wearout;

An example of these failure rate patterns is given in Fig. 21.2 which shows the mortality rate of humans, with phases of infant mortality, a middle age range with little variation in the mortality rate and finally, significantly increasing mortality rates with age. The shape of this graph gives rise to the term "bath tub" curve.

Determining the relevant pattern or patterns of failure for any particular asset, or for any particular failure mode of an asset, may require statistical analysis. Statistical analysis is outside the scope of this book, but some examples of the use of failure patterns are now discussed.

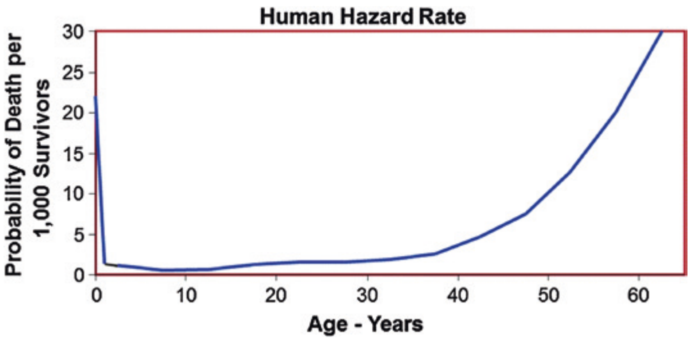

Fig. 21.2 The pattern of human mortality

21.7 Failure Pattern Discussion

21.7.1 Useful Life

The useful life of an asset is the period where its reliability is high and the risk of failure is low. Asset reliability can be relatively poor in the burn-in and wearout phases. This means that we need to avoid the burn-in and wearout phases, and ensure that random failures are kept to low levels. In general, we should investigate failures of any type to determine the root cause and take steps to avoid repetition.

The types of failure patterns are summarized in Fig. 21.3, which also indicates the types of causes. Not every item exhibits every pattern. If items are well manufactured with good quality control, burn-in failures can be minimized. Also, components should ideally be designed to last as long as, or longer than, the parent equipment, so that they do not reach the wearout stage. Thus many items will not reach wearout, particularly if they suffer little or no physical stress. Electronic items are typically in this category.

Burn In	Manufacture defect or faulty installation. Infant mortality. Occurs early in life. Rate decreases as early faults eliminated.
Random	Not related to item age or service time , so rate approximately constant through time. Often an external cause. Can also be failure of a complex system with many failure modes, such as electronic systems.
Wearout	Rate is related to and increases with age or service life. Causes include wear, ageing, corrosion, fatigue, creep, embrittlement of plastics.

Fig. 21.3 Age or operating life and failure rate patterns

21.7.2 Burn-in Failures

Burn-in failures are failures which occur early in the life of an asset, usually related to some form of manufacture or installation defect.

An example is a case where gearboxes on heavy haul trains were failing prematurely. At first the cause was unknown, but an investigation revealed that some of the gearboxes had fretting (wear patterns caused by frequent small movements) of the bearings. This was traced to the fact that these gearboxes had been transported by sea without the moving parts being secured. The fretting initiated serious wear when the gearboxes were put into service. The problem was tackled by ensuring that all the moving parts were secured before the gearboxes were transported from the manufacturer to the user.

Burn-in failures can be minimized by choosing well-developed and well-manufactured equipment and paying attention to acceptance testing and installation. Stress screening of electronic components and assemblies is a technique used to eliminate manufacture defects.

21.7.3 Random Failure Examples

Random failures are failures which occur as a result of events which are not related to the age or service life of the asset. They usually have an external cause.

An example is in a sugar refinery where sugar is filtered through a cloth. Failure of the cloth occurs when holes appear and it then has to be replaced. This may seem at first to be a wearout phenomenon, but examination showed that the failures of the cloth only occurred as a result of random inclusions of foreign matter in the raw sugar and were not related to the service time of the cloth.

In a manufacturing process, finned tube is made using an extrusion tool. Tools are found to break after making varying lengths of tube. The average length of tube per tool is 39 m. The operators suggest changing the tools just before this average length is reached. However, statistical analysis showed that the failure rate of the tools did not vary with the length extruded. Subsequent metallurgical analysis shows that breakage is due to random imperfections in the tube material and not to wear of the tools.

Reliability in the random failure phase can be enhanced by measures such as:

- Operate the equipment responsibly
- Do not overload
- Keep everything neat, clean, and tidy
- Do not leave stuff blowing in the wind
- Keep up-to-date with all preventive maintenance
- Fix minor faults or degradations promptly.

21.7.4 Wearout

Wearout failures are failures which arise due to age- or service-related deterioration. There are many examples of wearout failure modes. Common ones are the wear of vehicle tyres and brake pads. Other examples are the degradation of lubricants with time and use; corrosion of steel structures; fatigue of railway tracks or of any component subjected to repeated stress cycles.

Assets should be retired (or refurbished) at the onset of wearout. This means that we need to take measures to determine when wearout commences. In many cases, this can be done by an inspection or condition monitoring process. If so, we should use these techniques to determine a condition-based repair or replacement policy.

21.7.4.1 Statistical Analysis and Age Exploration

In some situations where parts cannot be effectively or economically monitored, we need to undertake statistical analysis or age exploration in order to determine an appropriate repair or replacement policy. This can occur when parts are not readily accessible, and particularly with failure modes such as:

- fatigue
- corrosion
- erosion
- insulation loss
- brittle decay of plastics.

Statistical analysis involves recording the age or operating life to which items run with and without failure and using techniques such as Weibull analysis[6] to estimate the point at which a rise in the failure rate becomes significant.

Age exploration involves running items to a gradually increasing age under controlled circumstances. If we do not want any in-service wearout failures—as for example with an airframe—the age exploration can be carried out under controlled laboratory conditions. Otherwise, we may have a selected population run under low-risk circumstances to act as the age exploration group.

21.7.5 Failure Mode Relative Importance

Studies of failure mode frequencies have highlighted the fact that straight counts of reported failures show larger numbers of random or burn-in failures than of

[6] P.D.T. O'Connor. Practical Reliability Engineering, ISBN: 0 470 84463 9.

wearout failures. However, the number of failures of a particular pattern does not necessarily reflect the importance of those failure modes. In aircraft, for example, wearout failure patterns of engine or structural components, are of much greater importance than the failure of electronic components for which duplicate systems exist. Our view of the importance of failure modes needs to take into account the consequences of failure.

21.7.6 Failure Interdependency

An additional factor to be considered in relation to reliability is that failures are not necessarily independent of one another. We can identify the following types of interdependencies.

- Independent—physically and statistically, e.g., individual light globes.
- Cascade—failure of one item triggers failure of others. Example, in Auckland, New Zealand, a power cable serving the central business district failed. Failure of one cable then caused an overload on others leading to further failures and a loss of all power to the district.
- Secondary damage—failure of one item impacts others, e.g., failure of wheel bearing results in damage to suspension and steering mechanism.
- Dependent—Power supply failure affects both an operating pump and the standby pump.
- Interrelated—Failure or degradation of one component causes another to wear more rapidly, e.g., seal failure admits sand to bearing causing wear.

21.7.6.1 Example

In 2008, a pipeline bringing gas from under the sea at Varanus Island in Western Australia ruptured and the gas ignited. The heat from the fire caused three other adjacent pipelines to rupture and extended the fire, which took 2 days to put out. Western Australia's gas supplies were cut by about 30 % for several months. Investigations showed that there was no corrosion coating on the pipeline on either side of the rupture point (Engineers Australia, November 2008).

21.7.7 Bad Actor

A bad actor is an item which fails between turnarounds. Identify and try to eliminate bad actors.

21.8 Failure Reporting and Corrective Action System (FRACAS)[7,8]

FRACAS is a formal system in which a range of specified parameters are reported when a failure occurs, and a specified systematic approach to corrective action is taken. US-MIL-STD-781 provides a description of FRACAS including details of the type of report to be generated when a failure occurs. Factors to be included in the report are:

- Failure/incident title
- Name of person raising the report
- Date and time of occurrence
- Equipment type
- Site and location of occurrence
- Contingency action taken
- Equipment odometer reading at failure
- Description of failure
- Description of effect of failure
- Repair action taken
- Operating conditions
- Cause of failure
- Date report raised
- Report of investigation
- Recommended actions to correct
- Follow-up testing or verification whether actions are effective
- Losses, time, cost
- Effects on safety
- Effects on environment
- Effects on production

Nonroutine work orders should always be examined as a basis for cause analysis and for determining actions to correct faults. This will typically involve understanding the equipment and possibly making changes, e.g., reduce overloading, design changes, and maintenance changes. There should be follow-up testing or verification to assess whether actions are effective.

[7] US-MIL-STD-781.

[8] ISO 55001 Clause 10.1 Non-conformity and corrective action: "When a nonconformity or incident occurs … the organization shall … react … take action … review … make changes if necessary …".

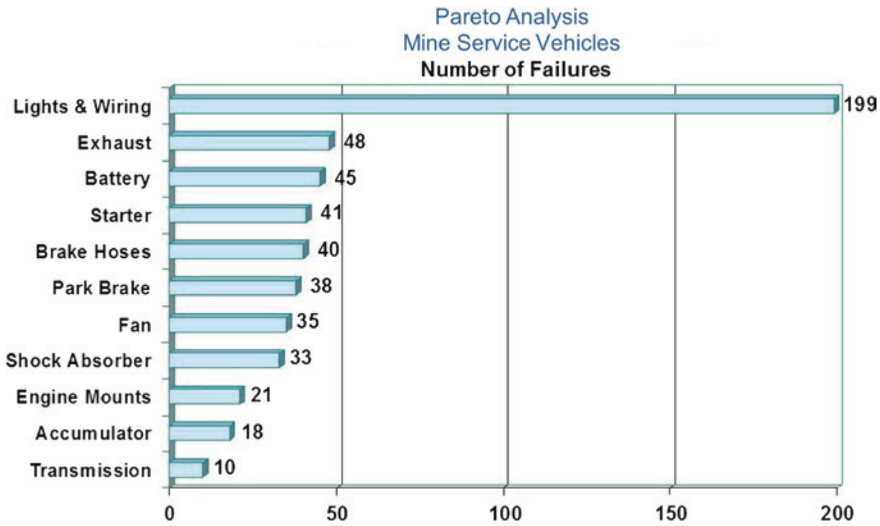

Fig. 21.4 Pareto analysis of mine service vehicle failures

21.9 Pareto Analysis

Pareto analysis, as applied to equipment failures, means ranking failure modes by frequency and cost. The most frequent and highest cost failure modes can then be addressed. Figure 21.4 is an example of frequency ranking.

In this application, the frequent problems with lights and wiring were reduced by replacing metal filament lights with LED lights which did not completely fail on impact, allowing the vehicle to continue in use until a convenient repair opportunity. Driving discipline was also addressed, as was road condition.

21.10 Failure Mode and Effects Analysis[9,10]

FMEA also known as *Failure Mode, Effects and Criticality Analysis* (FMECA) is a procedure used in assessing all the potential ways in which a product may fail, assessing the causes and effects of failure, and carrying out a numerical risk ranking. The technique is used in the design or manufacture of products. Recommendations to correct the failures or mitigate the effects are then made and acted upon. This technique can also be used in the investigation and correction of in-service faults and failures.

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[9] IEC 60812 Failure Mode and Effects Analysis.

[10] ISO 55001 Clause 10.2 Preventive action: "The organization shall establish processes to … identify potential failures …".

21.10.1 Common Failure Modes and Mechanisms

Examples of failure modes are given in Table 21.1.

21.11 Root Cause Analysis (RCA)[11]

Nullius in verba (Take nothing for granted). Motto of the Royal Society of London (1660).

RCA also known as Root Cause Failure Analysis (RCFA) is a formal approach to determining the cause of failures, with the intention of preventing future occurrences. The investigation of failures should be an organized activity involving personnel trained in investigative techniques and local operators and maintainers. There is some overlap between the concepts of Failure Recording and Corrective Action (FRACAS) and RCA. RCA is normally applicable to failures which require a degree of in-depth investigation.

When a failure occurs the following actions should be taken:

- Record the incident or ongoing problem.
- Take action to manage the issue in the short term.
- Asses the level of response needed—does the effect justify a substantial investment of time, effort, and money.
- A suitably skilled person should attend the site promptly.
- Preserve evidence, particularly broken parts.
- Record witness statements on site and in surrounding areas.
- Document observations, take photographs.
- Collect data and information systematically.
- Form an investigation team with specific roles and responsibilities.
- Develop hypotheses and test with data.
- Prepare a report with findings, conclusions, and recommendations.
- Implement recommendations to prevent or reduce the likelihood of a repeat incident.

In investigating an incident the primary aim is finding out why the failure occurred and in preventing it occurring again. Some useful questions to ask about a failed item are as follows:

- What is it supposed to do?
- Do we really need it?
- How is it supposed to work?

[11] Gano, Dean L., Apollo Root Cause Analysis. Apollonian Publications, Yakima, Washington, Second Edition 2003. ISBN: 1 883677 01 7.

Table 21.1 Failure modes

Breakage due to wear and tear
Breakage or jamming due to overloading, misapplied load, and excess tightness or looseness
Brittle failure, deterioration of plastic component due to loss of internal lubricating components due to aging and heat
Breakage due to alignment incorrect
Breakage due to out of balance causing vibration
Connection failure electrical
Corrosion, rust
Erosion of pipe or channel from fluid flow
Dirt or foreign matter in mechanism, pipe
Filter blocked or dirty
Foundations not firm or secure
Loose or missing nut, bolt, or fastener
Lubricant lacking, deteriorated or dirty, may cause seizure or overheating
Insulation breakdown
Water in oil
Design or manufacture fault
Fatigue failure
Vibration caused by wind
Vibration caused by rotating parts
Hose perished
Incorrect assembly
Leak in pipe, valve, tap, hose etc.
Loss of hydraulic fluid
Part missing, loose or falls off
Overheating due to lack of coolant, or cooling surface blocked
Seal leaking
Short circuit
Thermal stress causing fracture of pipe, vessel or structure
Welding fault causing fracture of pipe, vessel or fabrication
Drain blocked
Electrical insulation failure
Electrical connection failure
Consumable not replenished, e.g., detergent, disinfectant, lubricant
Catalyst regeneration required
Acid balance incorrect (or other chemical factor)
Vandalism, abuse
Storm damage, lightning strike, high wind
Accident damage
Operator, maintainer lacks knowledge of correct operation
Vermin—e.g., rat chews through insulation, bird makes nest in air inlet, toads block overflow
Power supply failure
Water supply failure

(continued)

Table 21.1 (continued)

Protective device failed
Fire damage
Flood/water damage
Wear
Fretting—repeated small movements caused by vibration, movement of ship, and movement of any supporting item

- If necessary, examine drawings;
- If all else fails, read the instructions;
- Observe a cycle of operations;
- Was it overloaded?
- Was it being misused?
- Was it operating within design parameters?
- Was it broken earlier?
- Has it received required maintenance?
- Is it a known fault?
- Is there a better way?
- Has a design change already been notified?

The extent to which it is desirable to pursue the root cause of a problem can vary. In many cases, it is best not to go to more depth than is necessary to get a solution but solving problems can sometimes lead to significant improvements.

21.11.1 Five Whys

Five Whys is a simple technique of RCA which can be quick and effective. It consists of asking 'Why' something happened, and then why the previous thing happened and so on, until an explanation is found. All the answers can be important.

For example: Shipment of iron ore is delayed.
First question: Why was the shipment delayed?
First answer: The stacker-reclaimer was slow in loading the conveyor.
Second question: Why was the stacker-reclaimer slow?
Second answer: Some of the ore was out of position in the stockpile
Third question: Why was some of the ore out of position?
Third answer: The dozer did not position the ore in time.
Fourth question: Why did the dozer not position the ore in time?
Fourth answer: The dozer is too small to cope with the workload.
Fifth question: Why is the dozer too small?
Fifth answer: Because it was not upgraded when the stacker-reclaimer capacity was increased.
The next step is to make a business case for upgrading the dozer.

21.11.2 Action and Condition Causes

To investigate a failure in more depth involves assessing *action causes* and *condition causes*. This can be tackled systematically as follows:

- Assemble knowledgeable team including users and maintainers.
- Identify symptoms of problem.
- Focus team on the specific problem.
- Define problem carefully. Which parts are affected, which are **not** affected.
- Under what conditions does the problem arise. Under what conditions does the problem **not** arise.
- Develop Cause Tree. Use stickers on white board.
- Consider both immediate causes (action causes) and contributory circumstances (condition causes).
- Avoid diverting to broader, unrelated issues.
- Brainstorm obtaining a solution, even if the root cause remains elusive.

21.11.3 Example—Pump Failure

In an underground copper mine, water gathers at the lower levels. For mining to proceed it is necessary to run pumps to clear the water. On a particular occasion, flooding occurred at mine level 23. This resulted in 24 h lost production. Figure 21.5 shows the first cause tree developed in a RCA of this failure. The failure was traced to a failure of pump number 14B. This was the Action Cause of the flooding. The Condition Cause was found to be a high level of mud in the water, which caused damage to the pump impeller, resulting in pump failure.

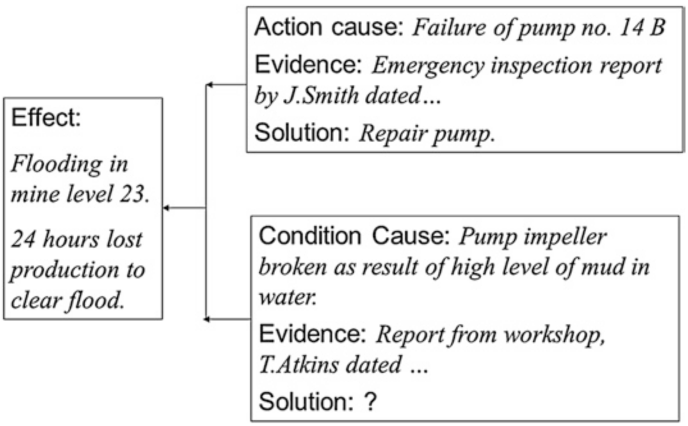

Fig. 21.5 Root cause analysis. Cause tree 1

21.11.4 Brainstorming a Solution

Some things to consider are as follows:

1. *Operation audit* Has it happened before? Evaluate operating procedures and practices. Is operation within design load or range. Consider cleanliness, tidiness, and housekeeping.
2. *Maintenance audit* Evaluate actual maintenance history, lubrication, wear, alignment, balance, maintenance tasks and frequency, ease of access, tools, procedures. Is there a symptom of a deeper problem?
3. *Design audit* Evaluate design standards and rules, capacity, loading, movement, methods, materials, fits and tolerances, design principles, environmental conditions.
4. *Management audit* Is there satisfactory management of operation and maintenance.

21.11.5 Example—Pump Failure Continued

Considering a solution to the pump failure problem, an essential action was to repair the pump. However, although this would solve the immediate problem it did not tackle the root cause. The root cause is shown in Fig. 21.6 as silt build up in the bund at level 14.

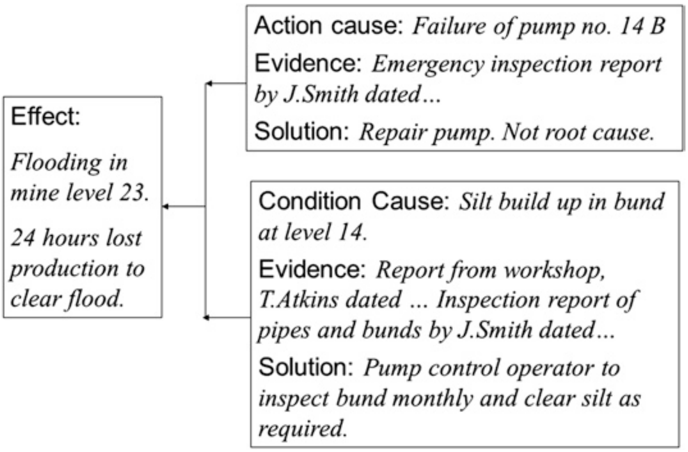

Fig. 21.6 Root cause analysis. Cause tree 2

21.11.6 Actions to Remedy

Task analysis dewatering pump:

- Repair pump
- Standby pump needed?
- Redesign sump to minimize silt?
- Provide small dredge to reduce excess silt when needed?

General case: Formulate improvement plans. Involve the user. May require changes to:

- operations;
- design;
- maintenance;
- equipment replacement;
- Use “fool proofing” (poka yoke) to help minimize errors in operation, set-up or handling.

Assess cost-effectiveness of improvement plans.

- Feed back results to workers—whatever the result may be.

21.12 Condition Monitoring

Condition monitoring involves using a diagnostic technique with the aim of detecting degradation of a function or component before failure occurs, with a view to taking remedial action to prevent in-service failure. Examples of monitoring techniques are the following:

- Vibration analysis
- Oil analysis for lubrication quality and contamination
- Temperature monitoring
- Acoustic (sound) analysis
- Ultrasonic detection for metallurgical weakness
- Insulation testing

Condition monitoring is known as *predictive maintenance* because it attempts to identify situations of impending failure and then to take action in advance so that the failure does not occur. The savings in avoiding in-service failures can be substantial when factors such as reduced unscheduled downtime, reduced labor, reduced parts usage, and reductions in secondary damage are taken into account.

Asset and maintenance managers need to be aware of the condition monitoring techniques which are most appropriate to the assets under their care. An early work which describes many condition monitoring techniques is R.A. Collacott,

Fig. 21.7 Condition monitoring techniques and medical parallels

Machine	Human Being
Human senses	Appearance - looks ill
Vibration analysis	Pulse, ECG
Thermographics	Temperature
Oil analysis	Blood sample
X-rays	X-rays
Ultrasonics	Ultrasonics
Pressure gauge	Blood pressure,
Performance monitoring	Stress test
Borescope	Endoscope
Megger – insulation testing	Angiogram
Strain gauge – movement of buildings or structures	Sprain

"Mechanical Fault Diagnosis". Over recent years there have been many advances in these techniques, particularly in terms of cheaper and more effective versions of the diagnostic tools. Figure 21.7 shows a list of condition monitoring techniques and the analogous technique used in medical diagnosis.

21.12.1 Delay Time or P-F Interval

An important factor in condition monitoring is that the detection of a degraded state must occur with sufficient time in hand to rectify the situation before in-service failure occurs.

An example is the case of wood rot of power poles. The condition of the poles deteriorates slowly over a period of years and the condition of a pole can be measured in terms of the amount of good wood left at any given stage. There is time to inspect the poles at intervals of several years and to determine which poles will need to be replaced soon.

Considering the general case, Fig. 21.8 illustrates schematically the deterioration in condition of an item from a "No fault" situation to one where a deteriorated condition is detectable. The item is monitored at intervals "I". The "Delay time" also known as the P-F Interval, (time from Potential to actual Failure) is the time that the fault condition takes to deteriorate into an actual failure. The idea is to set the monitoring interval to no more than half the delay time, so that the fault will be detected as shown in Fig. 21.8, in time for remedial action to be taken and the actual failure avoided.

21.12.2 Condition Monitoring Applicability

Condition monitoring is potentially applicable if the following conditions exist:

- Degradation becomes evident, indicating the existence of a potential failure mode that allows the progress of the failure conditions to be identified.
- Consistent failure patterns allow fault information to be diagnosed accurately.

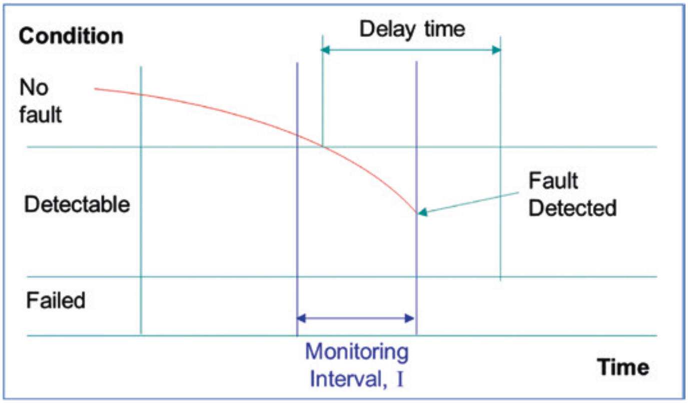

Fig. 21.8 Condition monitoring interval and delay time

- The time interval from the onset of potential failure to total failure (P-F interval or Delay time) is sufficiently long to accommodate the monitoring interval and the time taken for remediation/rectification. The monitoring interval is typically set to less than half of the P-F interval.
- Condition monitoring data can be collected with a high degree of repeatability.

21.12.3 Limitations

Limitations of condition monitoring occur when the time taken for a failure mode to progress from satisfactory operation to failure is short. This can occur with fatigue failures or brittleness of plastics. Another example is oil or grease condition where degradation can be rapid in hot or dusty environments.

21.12.4 Condition Monitoring Effectiveness

The effectiveness of a predictive maintenance technique can be assessed in terms of the reduction in in-service failures that it achieves. If in-service failures are still occurring, then the monitoring technique is of limited effectiveness and may need to be improved or supplemented by other actions such as age or service life-based replacement.

The "high-tech" nature of condition monitoring can lead to an assumption that it is 100 % effective, when in fact the effectiveness may be much lower than this. It is best to record data on the numbers of in-service failures which occur with the regime in place as a check on the effectiveness of the scheme.

Condition monitoring is a diagnostic tool and can have "Type 1" errors where an incipient failure is not detected and "Type 2" errors where a degraded condition is incorrectly indicated, or the wrong failure mode is diagnosed. For example, vibration analysis may not pinpoint the actual problem but can lead to time wasted in dismantling areas where there is no fault. Condition monitoring is very effective in many situations, provided that we are aware of its possible limitations.

21.12.5 Applications of Condition Monitoring

Some common applications are:

- Vibration monitoring of rotating equipment. Rotating machines when running correctly have moderate levels of vibration at certain frequencies, rather like a human heartbeat. The pattern of vibration is known as the vibration signature. Significant variations from the normal vibration pattern can be detected by instruments and warn that failure is imminent. Action can then be taken to check the machine and avoid a catastrophic failure.
- Thermographic inspection of electrical and mechanical equipment utilizing infrared measuring equipment. This detects variations from normal operating temperatures. For example, this can indicate a poor connection, insulation loss, or an open circuit in the electrical case and overheating of bearings or blockages or leaks in pipes or heat exchangers in a mechanical case.
- Wall thickness testing of piping and pressure vessels. This uses ultrasonic test equipment.
- Lubricant analysis for lubricating properties and impurities.
- Hot circuit fluid analysis.
- Trend analysis of cathodic protection and corrosion probes.

21.13 Reliability Centered Maintenance[12,13]

Reliability Centered Maintenance (RCM) is a systematic method for establishing a maintenance policy. This technique is suited to situations where an in-depth analysis is required. The application of RCM must involve an appropriate level of engineering authority, consistent with the technology of the application for which the maintenance policy is being developed. At the same time, the value of this technique lies in combining the knowledge of maintenance, engineering, and management staff in a structured process, providing benefits from the in-depth communication involved.

[12] Moubray, John, "Reliability-centered Maintenance", Industrial Press, New York.

[13] IEC 60300 3 11 Reliability Centered Maintenance.

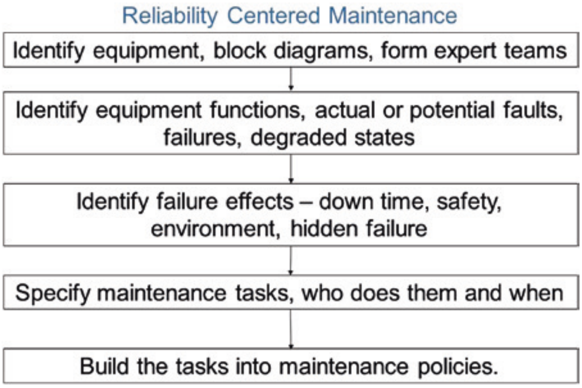

Fig. 21.9 Reliability centered maintenance concept

RCM provides a logical link between the equipment function, the need for reliability and safety, and the related maintenance policy. Figure 21.9 illustrates this.

21.13.1 Information Sources

Sources of information used in RCM include:

- Manufacturers documentation;
- Experienced maintenance personnel, particularly older staff, planners and supervisors;
- Records of previous maintenance activities;
- Maintenance and technical support staff;
- Suppliers;
- Consultants;
- Experienced operators;
- Operations records;
- Manufacturers local representative;
- Other users of same equipment;
- Statutory requirements; and
- Engineering standards and published guidelines.

21.13.2 Guidelines

- Select equipment to be analyzed.
- Form an "expert team" consisting of maintenance technicians, planners, supervisors, and engineers to carry out the RCM activity. A facilitator familiar with the RCM process will be needed.

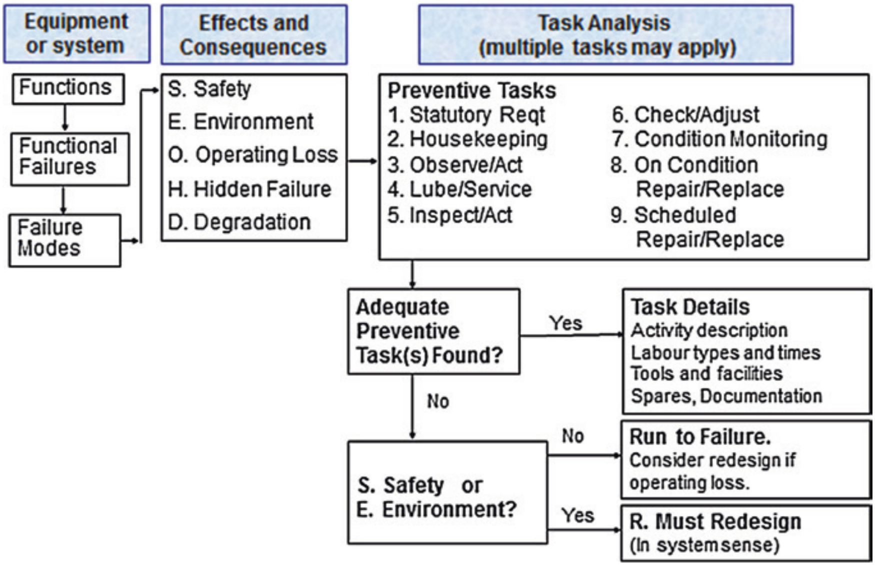

Fig. 21.10 Reliability centered maintenance flowchart

- Participation by the technicians is essential to achieve the "buy-in" necessary for successful implementation of the results.
- Take a fresh view, but be aware of existing maintenance plans and accept them as part of the RCM process where reasonable.
- Have an agreed format for the result using standard forms.
- Create and implement complete results in moderate-sized chunks.
- Do not go beyond the level of detail or design that your organization will handle.
- Consider the resources required to carry out each task as it is created, both at the task level and at an aggregate level.

The flow chart in Fig. 21.10 summarizes the RCM procedure.

21.13.3 Function and Functional Failure

A "function" of a machine or component is anything which it is supposed to do.

For example, the function of a brake is to slow and stop something. The function should include relevant technical values, e.g., a brake should stop a vehicle with specified load and speed within a specified distance. Understanding the function of a component is the key to understanding the reason for maintaining it correctly.

A "functional failure" is failure to perform a required function. This may not mean that an item fails in a complete physical sense.

In deciding the functions of an item, consider:

Basic role of the system, assembly or component, e.g., to provide power (engine), to transmit power (transmission), to hold vehicle in stationary position (hand brake).

Technical values associated with the function, e.g., engine to provide up to 150 kW of power, handbrake to hold vehicle on 1 in 4 gradient when vehicle loaded to 2 tonnes gross.

Efficiency/economy of function, e.g., fuel consumption not greater than 10 l per 100 km.

Structural integrity,

Environmental integrity,

Appearance and comfort,

Control,

Safety,

Whether there are **required** functions that are **not** provided, and

Whether there are **redundant** functions.

21.13.4 Functional Failure

A "functional failure" is failure to provide a required function.

Example: A pump in a given application is needed to pump water at 1,000 l/min. If the performance of the pump has deteriorated to the point where it can no longer deliver water at this rate, then the pump has a functional failure.

The pump may be working in a technical sense but it is failing to provide the required function. Of course it is also a "functional failure" if the pump fails completely.

21.13.5 Failure Mode

For each function of the selected item, we consider how it might or does **fail**.

We also identify all minor **faults**, undesirable conditions or degraded states, which may eventually progress into actual failures, for example:

- low oil level
- loose drive belt
- worn brush on electric motor
- leaking pipe.

21.13.6 Effects

For each failure or fault mode, we next consider the potential effects. The logic check sheet indicates five types of effects which must be considered:

- Safety
- Environment
- Operating or Production Loss
- Hidden Failures
- Degradation.

21.13.7 Hidden Failures

Hidden failures are failures which are not readily apparent to the operator of the equipment. Typically, they occur in protective devices. For example, if a burglar alarm fails, it will not be apparent, unless the alarm is tested, or a burglary occurs.

To check for a hidden failure it will be necessary to carry out an inspection or test of some kind.

21.13.8 Tasks

The next step in RCM is to determine maintenance tasks or actions which address the situation created by the failure modes and effects. RCM requires a review of all tasks to ensure that all the effects identified for a failure mode are met. The review of tasks may lead to the introduction of, or adjustments to such aspects as,

- inspection intervals,
- lubrication intervals,
- checks and adjustments,
- component or equipment replacement intervals or guidelines,
- condition monitoring regimes,
- repair pools and rotables provision,
- repair kits,
- check lists,
- troubleshooting guides,
- accessibility,
- tools,
- spare parts optimization,
- field repair teams provisioning,
- workshop facilities provisioning,
- redesign, and
- level of repair policy (Fig. 21.11).

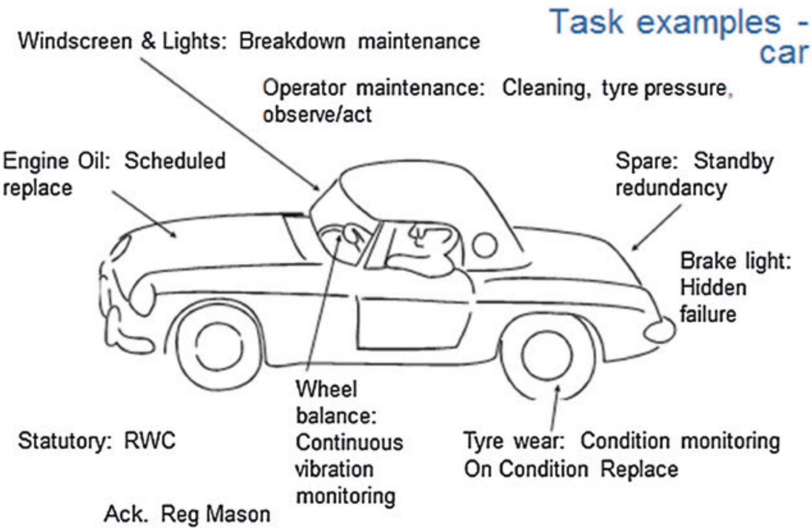

Fig. 21.11 Vehicle maintenance tasks

21.13.9 Reliability Centered Maintenance Conclusion

In conclusion, we see that RCM provides a systematic method for establishing a maintenance policy. The value of the technique lies in combining the knowledge of maintenance, engineering, and management staff in a structured process, providing benefits from the in-depth communication involved. RCM provides a logical link between the equipment function, the need for reliability and safety and the related maintenance policy.

21.14 Maintenance Policy Review

Most organizations already have maintenance policies in place. Maintenance Policy Review is a procedure for checking the suitability of the existing maintenance tasks. It is also known as Preventive Maintenance Optimization, or Reverse RCM. An RCM-style analysis is created, with the existing maintenance tasks being taken as a starting point and then considering the failure modes they are intended to address. This particularly includes inspection tasks. The analysis considers:

- the existing maintenance tasks,
- the range of failure modes that particular tasks are addressing,
- how effective is each task,
- are some tasks redundant,
- is there is duplication or overlapping of tasks,
- are there ways of combining tasks to reduce duplication or frequency,

- are other tasks needed, and
- can improvements be made to the effectiveness of remaining tasks.

There is a tendency for maintenance tasks to multiply over time in response to particular failures or incidents and this can result in overmaintenance. Maintenance Policy Review can offset this trend. It is important that the basic logic of normal RCM is respected, particularly in regard to safety considerations.

21.14.1 Example

At a minerals processing site, material is handled by crushers, conveyer belts, screens, and mills. A Maintenance Policy Review finds that several different groups (operators, mechanics, electricians, and condition monitoring technicians) are carrying out overlapping inspection processes. A rationalization of these processes produces considerable savings. The role of the operators is extended through additional training and the provision of basic monitoring equipment and time is freed up for the technicians to handle higher level work.

21.15 Availability

Availability is the proportion of time for which a machine is available for use. The simplest concept of availability applies when we have a single machine which is required continuously and which has an associated repair crew. The state of the machine is either "Up," that is running or available to run, or "Down," that is, failed. When the machine fails the repair crew repairs it. Figure 21.12 illustrates the situation. Availability of the machine is defined in the following terms.

Availability is the proportion of time for which a machine is available for use.
Down Time is time when equipment is not operable.
Up Time is time for which equipment is operable.

$$\text{Availability} = \text{Up Time}/(\text{Up Time} + \text{Down Time}) = \text{Up Time}/\text{Total Time}$$

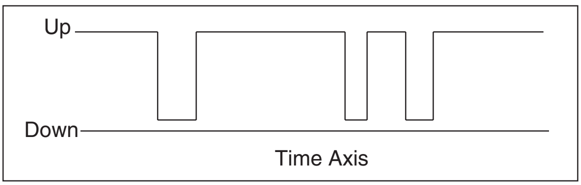

Fig. 21.12 Availability

Given the mean time between failures MTBF of the machine and the mean time to repair MTTR, then the Availability, *A*, is given by:

$$A = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

To achieve a high availability, the MTTR must be much shorter than the MTBF. Availability can be improved by increasing the MTBF or decreasing the MTTR.

21.15.1 System Availability

Most practical situations are more complex than the single machine case. Also, the time taken to get a failed machine running is not just the active repair time, but can include many elements, such as those in Fig. 21.13. Thus, in estimating availability, we may need to consider the Mean Administrative and Logistic Delay Time rather

Element of Down Time	**Down Time Reduction Activities**
Diagnostic delays	Improved operator training. Improved instrumentation.
Reporting delays.	Improved communications.
Travel time for maintenance person to breakdown location.	Improved transport. Repair person located nearer to breakdown location.
Travel time for machine to repair facility.	Better transport arrangements.
Inspection, diagnosis, repair cost estimating and documentation.	Staffing, equipment, training, documentation, troubleshooting techniques.
Repair decision.	Delegation of authority. Speed of response.
Hazard analysis. Obtaining permit to work	Hazards documented. Good liaison between production and maintenance.
Awaiting spares.	Inventory control. Resupply and purchasing policy.
Awaiting labour. Awaiting repair facilities, tooling, technical information.	Vary staffing by trade, shift, sub-contract, training, multi-skilling. Reassign jobs to another maintenance area.
Active repair time.	Improve maintainability. Study repair methods and procedures, equipment.
Inspection and testing.	Staffing, instrumentation.
Travel to required location.	Transport arrangements.
Installation time. Run up time.	Staffing, training, multi-skilling, methods, procedures.

Fig. 21.13 Elements of downtime

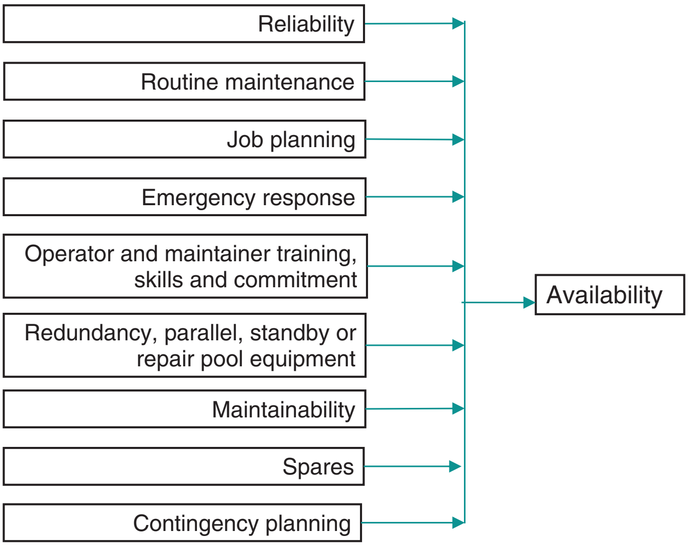

Fig. 21.14 Inputs to availability

than the Mean Time To Repair. Besides these specific types of delay, general factors which contribute to the achievement of availability are shown in Fig. 21.14.

21.15.2 Cost of Downtime

The potential types of cost associated with failure are indicated in Fig. 6.1. The cost of failure and of downtime is the basic driver for maintenance and influences priorities for maintenance. The cost of downtime is hard to quantify, and varies considerably with circumstances, but awareness of the cost of downtime is important to good management, because it provides a sound basis for evaluating the trade-off between maintenance costs, capital equipment expenditure, and business profitability. If managers are not aware of the cost of downtime, they may see maintenance as purely a cost element which can be cut without regard to flow on effects.

21.15.3 Availability When Needed

Many systems do not require 100 % availability all of the time. Preventive maintenance can be scheduled to take place in times of low demand. Breakdown maintenance can continue in low demand periods, such as weekends or holidays. Repair support can be increased in periods of high demand so as to minimize the effects of outages.

For example, in electricity generation, demand fluctuates with time of day and season of year. Capacity required can be forecast, and individual generators brought on stream at particular times. Equipment shutdowns are scheduled for periods of low demand. Available capacity is normally designed to cover the unexpected loss of the largest generator currently running. Similar considerations apply in transmission systems. This approach is known as n − 1 *redundancy*, indicating that the loss of one component should not cause a loss of supply.

21.16 Availability Related to Total Time

Most equipment does not operate on a 24 h 7 days a week basis, and there are scheduled times of nonuse, scheduled maintenance times, and other times when machinery is not required. The definition of availability in these circumstances requires a consideration of how the total time available is partitioned. Figure 21.15 illustrates this.

The following availability measures can then be defined.

$$\textit{Availability (When Required)} = 1 - M3/(SP - NR)$$
(of equipment from maintenance when required)

$$\textit{Maintenance Effectiveness} = 1 - (M1 + M2 + M3)\big/ S$$
(100 % if no maintenance)

$$\textit{Availability (Total)} = 1 - (M1 + M2 + M3)\big/ T$$
(of equipment from maintenance as related to total time)

$$\textit{Availability (When Required)} = 1 - LP/(SP - NR)$$
(all causes)

$$\textit{Relative Maintenance Losses} = M3\big/ LP$$
(lost time due maintenance as a proportion of all lost time)

There is also a possibility of opportunistic maintenance in nonscheduled time.

21.17 Maintenance Effectiveness

The effectiveness of maintenance relates to how well the effort put into maintenance translates into reliable and available equipment. Figure 21.16 shows factors that influence the effectiveness of maintenance. The skill of the maintenance workforce in relation to the tasks on hand is a key factor, and training and

<table>
<tr><td colspan="7">Total Time, T</td></tr>
<tr><td colspan="6">Scheduled Time, S</td><td>Non-scheduled time</td></tr>
<tr><td colspan="5">Scheduled Production Time, SP</td><td>Scheduled Maintenance Time, M1</td><td>Non-scheduled time</td></tr>
<tr><td>Actual Production Time, AP</td><td colspan="2">Lost Production Time, LP</td><td colspan="2">Production Not Required Time, NR</td><td>Scheduled Maintenance Time</td><td>Non-scheduled time</td></tr>
<tr><td>Actual Production Time, AP</td><td>Lost Prod Time due Maint. M3</td><td>Lost Prod Time due Other, LO</td><td>Not required other</td><td>Opportunistic Maintenance Time, M2</td><td>Scheduled Maintenance Time, M1</td><td>Non-scheduled time</td></tr>
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Fig. 21.15 Availability related to total time

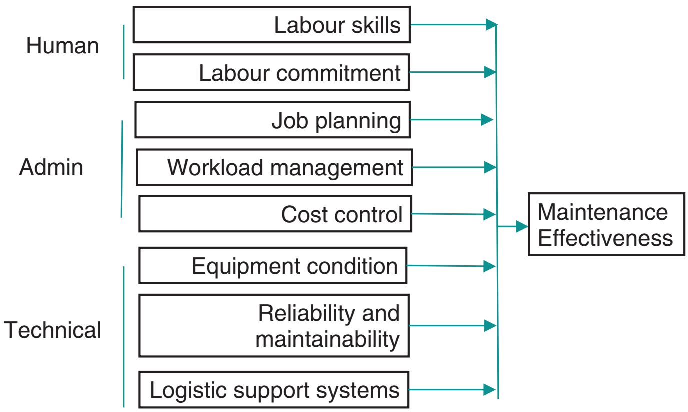

Fig. 21.16 Inputs to maintenance effectiveness

continuity on the job are therefore important. Possibly, the most important factor of all is the degree of commitment or motivation of the workforce—an indicator of lack of commitment is absenteeism. The degree of commitment is influenced by the other factors in the figure, since lack of cleanliness, poor planning, inherently unreliable equipment, and poor logistic support will lead to poor morale.

Maintenance personnel generally welcome being involved in work on improving reliability and maintainability, such as RCA, diagnosis, and condition monitoring. However, a tendency to replace basic maintenance by sophisticated but ineffective activities should be resisted.

21.18 Maintenance Load

The maintenance load generated by a system is the resource requirement for maintenance of the system per unit of service. For example, for an aircraft this is the maintenance hours per flying hour. The maintenance load will consist of routine and nonroutine activities, of which the latter can only be estimated on the basis of some operating experience. It may also be expressed in cost terms, such as maintenance $ per flying hour.

21.19 Maintenance Regime

It is important to have an established maintenance regime, and for this to be documented, adhered to, and records kept. Conforming to the manufacturers recommendations, meeting all regulatory requirements, and staying within warranty claim boundaries are good basic ideas. Variations from this need a reason. Be confident about what you can tell the judge in a court case.

The maintenance regime specifies the details of what maintenance is done routinely, by whom and at what frequency, and the procedures for both routine and nonroutine maintenance.

21.20 Maintainability[14,15]

Maintainability relates to the ease or difficulty with which an item can be repaired when it fails. A basic factor in maintainability is the *Mean Time to Repair* (*MTTR*). This is defined as the average length of active time taken to repair an item which has failed. An item which is easy to repair will have a short MTTR, and an item which is hard to repair will have a longer MTTR. As a more formal measure, it is the proportion of repairs that are completed within a specified *maintenance time constraint*.

21.20.1 Design for Maintainability

Maintainability is a design factor which competes with other requirements such as low initial cost, good performance, and reliability. For example, it may improve the maintainability of a chemical reactor vessel to have an access plate in a certain

[14] IEC 60300 3 10 Maintainability.

[15] Blanchard, Benjamin S and Lowery, E.Edward. "Maintainability", Mcgraw-Hill 1969.

spot, but this may also increase the cost and reduce performance because of reduced allowable pressure, and may decrease reliability, because of the need for seals which are less reliable than a solid wall. In designing for maintainability, the general aims are to reduce total maintenance load and to reduce downtime when it occurs.

A good design will minimize and simplify maintenance tasks, and provide predictability in maintenance requirements. Specific features which promote good maintainability include ease of access by technicians; visibility; ease of testing; interchangeability of components or modules; provision of good maintenance documentation and diagnostics. Some further details of techniques used to provide good maintainability are as follows:

- *Access* Provide good access for maintenance.
  - Access plates.
  - Use hinged panels.
  - Use roll out drawers…
- *Modularise* Example: Maintainability of an electronic device may be improved by making it in the form of detachable boards plugged into a base. The plugs, however, may have low reliability when compared with permanent joints.
- Minimize need for special tools.
- Minimize range of tools required.
- Provide failure signals, warning signals, and built-in sensors.
- Provide troubleshooting, diagnostic aids and plans.
- Built-in monitoring points.
- Provide good instrumentation.
- Label assemblies.
- Provide operation and calibration information on labels.
- Use easily replaceable, expendable components, e.g., flywire door.
- Prevent faulty assembly (poka yoke).
- Provide handles or other lifting points.
- Provide castors.
- Lubrication points visible and accessible.
- Adjustment points visible and accessible.
- Provide spare fuses or equivalent reset.
- Provide adequate illumination.
- Redundancy, e.g., standby light bulb with switch.
- Help desk, online maintenance support, and portable computer with workshop manuals and drawings, etc.

An example of poor design for maintainability is shown in Fig. 21.17.[16]

[16] Blischke W.R. and Murthy D.N.P. Case studies in Reliability and Maintenance, Wiley, 2003.

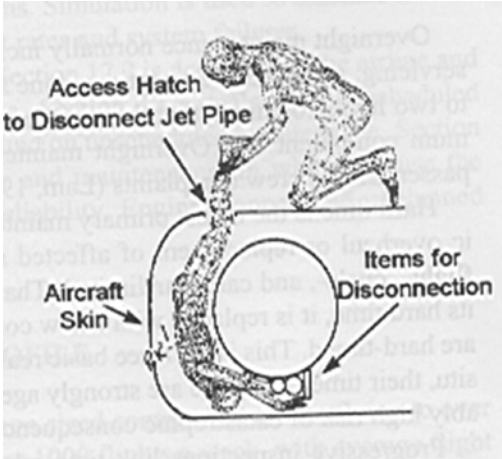

Fig. 21.17 A maintainability nightmare

21.21 Maintainability Measure

In order to specify, measure, and compare maintainability of items, we need a definition of maintainability as a measurable quantity. For this purpose, we define maintainability as a probability that an item can be restored to operating condition within a specified interval of time, when maintenance is performed in accordance with prescribed procedures and resources. The following definition is adapted from Society of Automotive Engineers Standard SAE JA1010.

Maintainability is the probability that an item will be repaired within a specified time, referred to as the *maintenance time constraint*.

The Maintenance Time Constraint is set in relation to operational circumstances, such as, aircraft turn around time. As a property of the item itself, maintainability is related to Active Repair Time. As a property of a system, maintainability is related to total downtime.

The average value of the time to repair is known as the MTTR. If the distribution of the time to repair is negative exponential, the repair rate is constant and is the reciprocal of the MTTR. Define

MTTR = Mean Time to repair
μ = Repair Rate

Then for the exponential model we have

$\mu = 1/\mathrm{MTTR}$
$M = 1 - \exp(-\mu t)$

where M is the Maintainability and t is the Maintenance Time Constraint. Thus, if we have data from which we can estimate the Mean Time To Repair, then we can calculate the corresponding maintainability with reference to our maintenance time constraint.

21.22 Desert Song

"So where did you go after Norway, Pop?" asked Jock on his next visit to his granddad. Jock really enjoyed hearing his Pop's old stories but it was hard to get him going on them.

"What sort of stuff are you working on now?" said Pop, diverting the question.

"It's about sustaining our in-service assets, but I think you would call it maintenance," said Jock; and after a pause Pop decided there were some things about maintenance that Jock ought to know.

"We were in North Africa," said Pop. "You know those films with John Wayne firing a machine gun from the hip from a moving tank?"

"Yes," said Jock

"Well it's not like that. The fact is that tanks get stuck or break down pretty easily. There is always soft sand or mud, unexpected gullies, rocks or concrete in the wrong place. It's surprising how easily they can throw a track or strip the final drive or just get into a spot where they can't move. And that's not counting enemy action or mines. After a day's fighting in the desert dozens of tanks on both sides would be broken down somewhere. But somehow the Germans had most of theirs up and running again by next morning. It had us flummoxed at first.

"We found that they had the field maintenance angle well worked out. They had recovery vehicles with a winch and a spade which could pull a tank out of any spot, and repair teams trained and equipped with all the right tools and spares.

"At that time we didn't even have a mechanical and electrical engineering corps at all. We just had fitters attached to the supply regiment.

"And we loved their petrol cans—jerry cans we called them. Our cans were so flimsy that they would start leaking at the drop of a hat."

"Pretty bad eh," said Jock.

"Before the war our staff blokes must have still been dreaming of the old cavalry days. They finally picked up on it after the Germans looked like they would make it to Cairo. By Alamein we began to get some better equipment through and a mechanical and electrical engineering corps was formed. Later when the Americans came in with the half-tracks we got our forward repair teams running too."

21.23 Exercises

21.23.1 Self-Assessment Exercise

1. Define reliability.
2. Define MTBF.

3. Define Failure Rate.
4. What are toolbox meetings and why are they important?
5. What are the three common failure rate patterns?
6. What does FRACAS stand for?
7. What is Pareto analysis?
8. What is RCA?
9. What is the five whys RCA technique?
10. What is Condition Monitoring?
11. What is RCM?
12. What are hidden failures?
13. What is maintenance policy review?
14. What is availability?
15. What is meant by the maintenance load of an asset?
16. Identify five factors which are important for good maintainability of an asset.

21.23.2 Pacific Earth Moving Pt 6: Reliability and Availability

In addition to routine maintenance activities, Pacific Earth Moving needs to achieve high standards of equipment availability in its mobile plant fleet in order to meet targets set in its contracts with client companies.

At present the availability levels are below target. You have been asked to advise the company on what methods or techniques should be introduced in order to improve the reliability and availability for the company's plant. Give your answer in dot point form, stating the features of each approach and indicating the potential benefits and costs.

21.23.3 Cost of Downtime

A single conveyor brings mineral ore from a mine to the surface. The conveyor operates full time, which in this case is 48 weeks/year, 48 h/week. Extension of this working period is not practicable. Experience shows that conveyor availability is 87 %. The sales value of production is $30,000,000 per year. Estimate the hourly cost of downtime in terms of lost sales revenue. The conveyor system uses minimal consumables.

21.23.4 Availability Related to Total Time

A plant makes two types of coiled spring, Small and Large. The standard production times are:

Small 3 min per spring
Large 4 min per spring

The plant works nine 8 h production shifts per week, with an additional maintenance shift of 8 h.

In a given week, the following data are recorded.

Production: Smallsprings 578
Large springs 492

Unscheduled Downtime due to Maintenance: 7 h 30 min

Calculate the ratios referred to in Fig. 21.15:

$$\textit{Availability (When Required)} = 1 - M3 / (\mathrm{SP} - \mathrm{NR})$$
(of equipment from maintenance when required)

$$\textit{Maintenance Effectiveness} = 1 - (M1 + M2 + M3) / S$$
(100 % *if no maintenance*)

$$\textit{Availability (When Required)} = 1 - \mathrm{LP} / (\mathrm{SP} - \mathrm{NR})$$
(all causes)

$$\textit{Relative Maintenance Losses} = M3 / \mathrm{LP}$$
(lost time due maintenance as a proportion of all lost time)

How much time is lost during production shifts for reasons other than maintenance? Assume that there is no “Not Required” time.

21.23.5 Hydraulic Faults

In an application involving the extensive use of hydraulic machinery, verbal reports indicate frequent failure of hydraulic systems. Technicians say that hoses are often the source of problems. What would you do?

21.24 Exercise Solutions

21.24.1 Self-Assessment Exercise Solution

1. *Define reliability.*
   Reliability is the ability of an item to perform a required function under stated conditions for a specified period of time.
2. *Define MTBF.*
   MTBF is the average time for which an equipment operates between failures occurring.

3. *Define Failure Rate*.
   Failure rate is the number of failures per unit of operating time.
4. *What are toolbox meetings and why are they important*?
   A toolbox meeting is a meeting of maintenance personnel with supervisors and planners, typically held weekly as part of the maintenance planning and scheduling process. Feedback from maintainers forms a valuable source of information relating to in-service asset reliability. The key step here is for management to listen to the feedback and to take corresponding action where warranted.
5. *What are the three common failure rate patterns*?
   Burn-in, random, and wearout.
6. *What does FRACAS stand for*?
   Failure Reporting and Corrective Action System.
7. *What is Pareto analysis*?
   Pareto analysis, as applied to equipment failures, means ranking failure modes by frequency and cost.
8. *What is RCA*?
   RCA also known as RCFA is a formal approach to determining the cause of failures, with the intention of preventing future occurrences.
9. *What is the five whys RCA technique*?
   Five Whys is a technique of RCA which consists of asking "Why" something happened, and then why the previous thing happened and so on, until an explanation is found. All the answers can be important.
10. *What is Condition Monitoring*?
    Condition monitoring involves using a diagnostic technique with the aim of detecting degradation of a function or component before failure occurs, with a view to taking remedial action to prevent in-service failure.
11. *What is RCM*?
    RCM is a systematic method for establishing a maintenance policy.
12. *What are hidden failures*?
    Hidden failures are failures which are not readily apparent to the operator of the equipment.
13. *What is maintenance policy review*?
    Maintenance Policy Review is a procedure for checking the suitability of the existing maintenance tasks.
14. *What is availability*?
    Availability is the proportion of time for which a machine is available for use.
15. *What is meant by the maintenance load of an asset*?
    The maintenance load generated by a system is the resource requirement for maintenance of the system per unit of service.
16. *Identify five factors which are important for good maintainability of an asset*.

    - Accessibility
    - Modularity
    - Diagnostic aids

- Redundancy
- Labeling
- Other items in Sect. 21.21.

21.24.2 Pacific Earth Moving Part 6: Solution

- System of review and response to operator reports of losses or faults
- Incident reporting and management
- FRACAS
- FMEA
- RCM or related review of maintenance regime
- RCA
- Condition monitoring, oil, vibration, thermal, etc.
- Maintainability analysis
- Spare parts service level review, value turns, and control settings
- Repair pools and rotables provision and planning
- Component replacement policy analysis
- Forward repair teams
- Workshop facilities provision
- Equipment replacement planning.

21.24.3 Cost of Downtime

$$\begin{aligned}\text{Hours per year} &= 48\ \text{weeks} \times 48\ \text{h} \times 87\,\%\ \text{availability}\\ &= 2{,}004\,\text{h}\\ \text{Cost of downtime per hour} &= \$30{,}000{,}000 \big/ 2{,}004 = \$15{,}000.\end{aligned}$$

21.24.4 Availability Related to Total Time

Scheduled Time = S = 80 h = 4,800 min
Scheduled Production time = SP = 4,320 min
Scheduled Maintenance time = $M1$ = 480 min
Lost Prod. time due to maint. = $M3$ = 450 min
Not Required time = NR = 0
Opportunistic maint. time = $M2$ = 0
Actual Production time = AP = 578 * 3 + 492 * 4 = 3,702 min
Lost production time = LP = SP – AP = 618 min

A(WRmaint) = 1 − $M3$/SP = 89.6 %
Maint. Effectiveness = 1 – ($M1 + M3$)/S = 80.6 %
A(WRall causes) = 1 − LP/SP = 85.7 %
Lost Prod. Time other = LP – $M3$ = 168 min
Relative Maint. Losses = $M3$/LP = 72.8 %.

21.24.5 Hydraulic Faults Solution

Check the work order history to assess the significance of the problem. Carry out pareto analysis of hydraulic failures to check for main issues. Hoses are found to be the main source of problems. Carry out an audit of hose condition. Replace hoses in poor condition. Define and disseminate condition and inspection and replacement standards for hoses. Improve training. Ensure correct hoses are fitted, that fittings are sound, and that operators are aware of possible damage to hoses and are trained to avoid such damage. Operators and inspectors to report leaking or damaged hoses, with follow-up repair.