Introduction to RAM

What is RAM?

RAM refers to Reliability, Availability and Maintainability. Reliability is the probability of survival after the unit/system operates for a certain period of time (e.g. a unit has a 95% probability of survival after 8000 hours). Reliability defines the failure frequency and determines the uptime patterns. Maintainability describes how soon the unit/system can be repaired, which determines the downtime patterns. Availability is the percentage of uptime over the time horizon, and is determined by reliability and maintainability.

Why choose RAM Analysis?

RAM has a direct impact on profit through lost production and maintenance costs. The main objectives of RAM are to increase system productivity, increase the overall profit as well as reduce the total life cycle cost — which includes lost production cost, maintenance cost, operating cost, etc.

Some significant figures are:

- As much as $100,000 per hour typical production losses can be sustained in base chemical plants due to non-availability
- In oil refineries, production losses are millions of dollars per year for every 1% of non-availability
- In oil refineries, the maintenance staff are up to 30% of total manpower
- Maintenance spending is one of the largest parts of the operational budget after energy and raw material costs
- Each year over $300 billion is spent on plant maintenance and operations by US industry, and it is estimated that approximately 80% of this is spent on systems and people to correct the unplanned failure of machines (Engineering Maintenance, 2002)
- The operation and maintenance budget request of the US Department of Defence for the fiscal year 1997 was on the order of $79 billion

RAM analysis is essential to the system profitability. Even small improvements in the effectiveness of RAM schemes make large additions to the bottom line.

Role of RAM Analysis

Fig.1 illustrates the interactions and applications of RAM analysis. For an existing process, maintenance data are usually recorded in the CMMS (Computerised Maintenance Management System). These data can be analysed through qualitative and quantitative approaches, as shown in Fig.2.

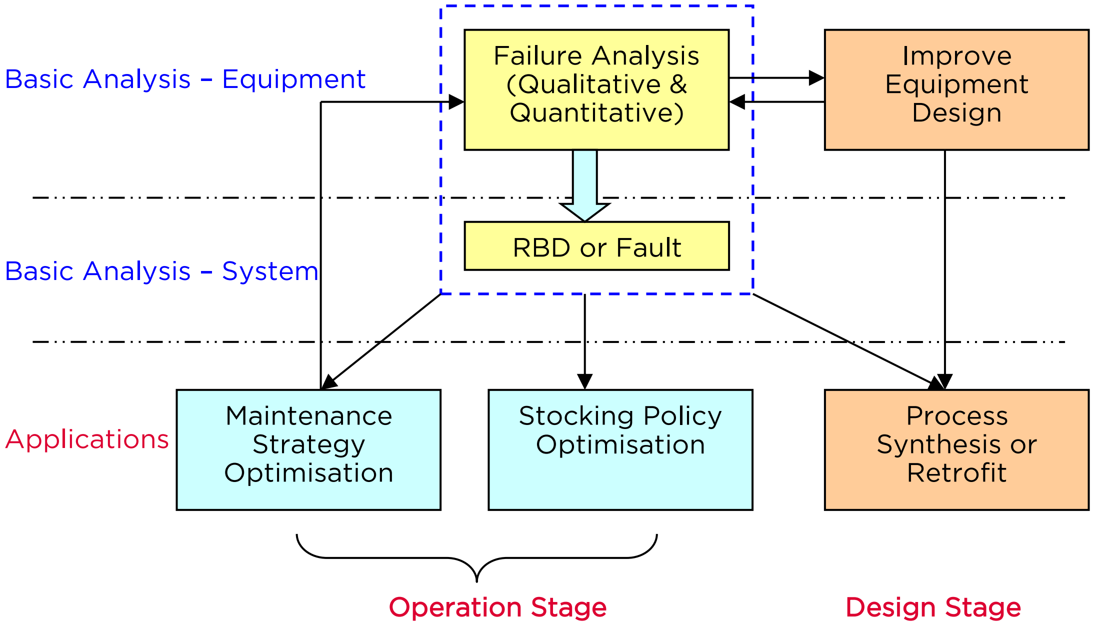


Fig.1 RAM Analysis Cycle

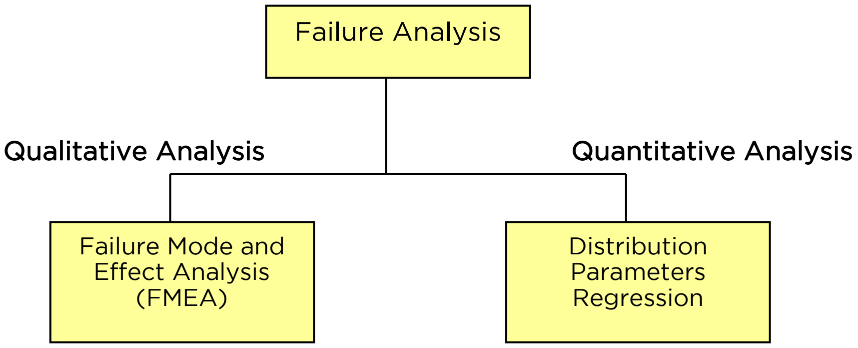


Fig. 2 Failure Analysis

Failure mode and distribution parameters can be obtained for each unit in the system. Reliability Block Diagrams (RBD) or Fault Trees (FT) can be used to represent the logic relationships between component failures and system failures, and provide the basis for a RAM study. With the failure distribution data input into an RBD/FT, engineers will be able to understand the RAM performances of the current system and carry on further developments and optimisations. In fact, there is a direct relationship between RBD and FT, but most engineers find RBD easier to use, as it can be more easily related to a process flowsheet. The approach to RAM analysis adopted by Process Integration Limited exploits RBDs.

In the operation stage, RAM analysis can be implemented to optimise maintenance strategy as well as stocking policy for spare parts. The maintenance strategy will then affect the failure records in the CMMS, which in turn help engineers revise the maintenance strategy through time. New failure records will be saved in the CMMS during the operating stage.

In the design stage, RAM analysis can be integrated into the design of the system configuration, which will ensure the optimum design with balanced RAM performance and total investment. Moreover, the qualitative and quantitative analysis of process unit failures can help designers to modify the structure of a specific process unit to improve the process design.

RAM analysis run throughout both operating and design phases to enable the process to achieve high profitability.

Benefits of RAM Analysis

The following benefits can be obtained from RAM analysis.

- Decision making
  - What maintenance policy should be applied
  - Investment decisions on maintenance
- Resource utilisation
  - Inspection intervals
  - Optimum spare part purchasing
- Appropriate maintenance scheduling
  - Understanding the financial implications of maintenance
  - Decision making based on modelling
- Cost management
  - Managing the cost related to unavailability
  - Cost of maintenance
  - Etc.
- Integration with other business activities
  - All projects on a site have an effect on process RAM
  - RAM needs to involve the whole organization
- Meeting the business demand
  - Reduce outages caused by breakdowns
  - Reduce the loss of revenues caused by unavailability
- Etc.

RAM Analysis Tools

There are several tools to conduct RAM analysis in different stages and for different purposes, as shown in Figure 3.

FMEA (Failure Mode and Effects Analysis) or FMECA (Failure Mode, Effects and Criticality Analysis) can be used to identify equipment failure modes and their system effects. FMEA/FMECA provides the basis to system failure analysis. On system level, Event Tree (ET), Fault Tree (FT) and Reliability Block Diagram (RBD) can be used to represent the logic relationships between individual equipment failure modes and system failure modes.

An Event Tree uses binary branching to identify the events leading to system failures or successes. In a Fault Tree, system failures can be expressed in terms of combinations of component failure modes, as illustrated in Figure 4a. A Fault Tree is part of Event Tree and can be transformed from an Event Tree. An RBD, as illustrated in Figure 4b, is a logical inverse of a Fault Tree. As shown in Figure 4b, blocks are used to represent component failures or failure modes for a certain component. The approach to RAM analysis adopted by Process Integration Limited exploits RBDs because most engineers find the RBD easier to use, as it can be more easily related to a process flowsheet.

With distribution parameters input into an RBD (or ET or FTA), system RAM performance will be obtained by simulations.

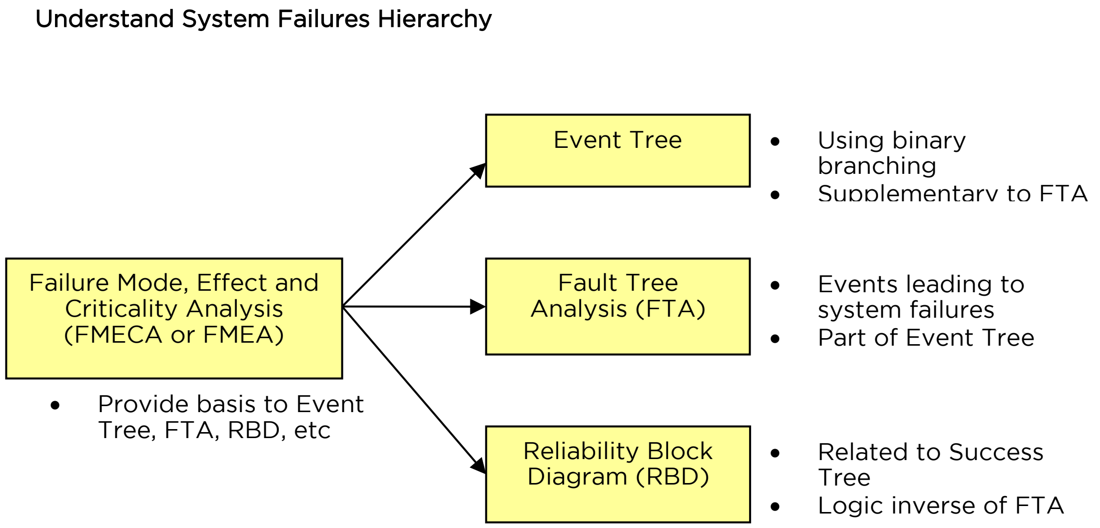
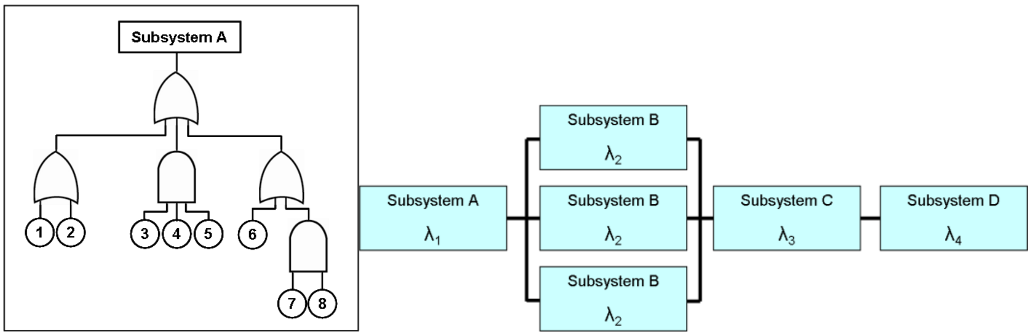


Fig.3 Different RAM Analysis Tools



a) Fault Tree b) Reliability Block Diagram

Fig.4 Fault Tree and Reliability Block Diagram Examples

Deterministic or Probabilistic Modelling

A RAM study is conducted through a probabilistic approach, which is fundamentally different from a deterministic approach. The difference is illustrated by an example. As shown in Table.1, 41 failures are recorded in 20 years. Table.2 lists other necessary data.

Table.1 Failure Records

Failure Record					
No	Time	No	Time	No	Time
1	02/05/1990	15	03/04/1996	29	28/01/2002
2	29/05/1990	16	20/10/1996	30	20/09/2002
3	07/07/1990	17	19/09/1997	31	23/05/2003
4	19/11/1990	18	02/09/1998	32	31/01/2004
5	07/04/1991	19	07/02/1999	33	19/10/2004
6	04/09/1991	20	22/07/1999	34	08/07/2005
7	04/02/1992	21	11/01/2000	35	08/04/2006
8	11/07/1992	22	11/04/2000	36	09/01/2007
9	28/01/1993	23	14/07/2000	37	04/11/2007
10	03/09/1993	24	22/10/2000	38	15/09/2008
11	13/04/1994	25	11/05/2001	39	07/01/2009
12	30/11/1994	26	04/07/2001	40	10/05/2009
13	03/04/1995	27	30/08/2001	41	21/05/2010
14	26/09/1995	28	12/11/2001		

Table.2 Maintenance and Cost Data

Mean Time To Repair (days)	5
Mean Time of PM (days)	1
CM Cost (K$ per action)	10
PM Cost (K$ per action)	2
Lost Production Cost (K$/day)	240

Maintenance costs in Table.2 are associated with the penalties of consequent damages to other units.

a) Deterministic Approach

According to the data in Table.1, Mean Time Between Failure (MTBF) = 7142 day/ 40 = 178 day. Using a deterministic approach, it is assumed the component will fail every 178 days, as shown in Fig.5.

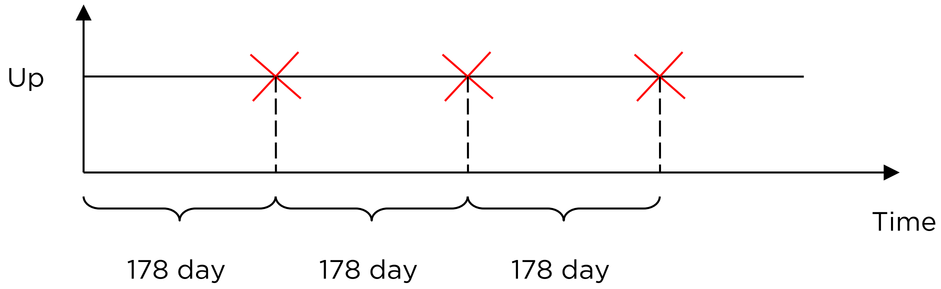


Fig.5 Failure Analysis using Deterministic Approach

To reduce unexpected failures, two preventive overhaul schemes are considered:

1. Preventive overhaul at MTBF – 178 days
2. Using rule of thumb: preventive overhaul at 80% of MTBF – 145 days

Based on the economic data, total annual costs with different maintenance policies are listed in Table.3. The cost comprises corrective maintenance cost, preventive maintenance cost and lost production cost. As a result, preventive overhaul at MTBF reduces the cost by 19%. If rule of thumb is applied and overhaul at 80% of MTBF, the total cost is reduced by 23%.

But it is dangerous to use the rule of thumb for every unit, since each unit has different failure distribution patterns as well as different maintenance cost, associated penalty cost, etc. It is not possible to find a “golden rule” which can be applied for all of the process units. Costs could even be increased with a wrong rule.

Table.3 Total Cost of Different Policy

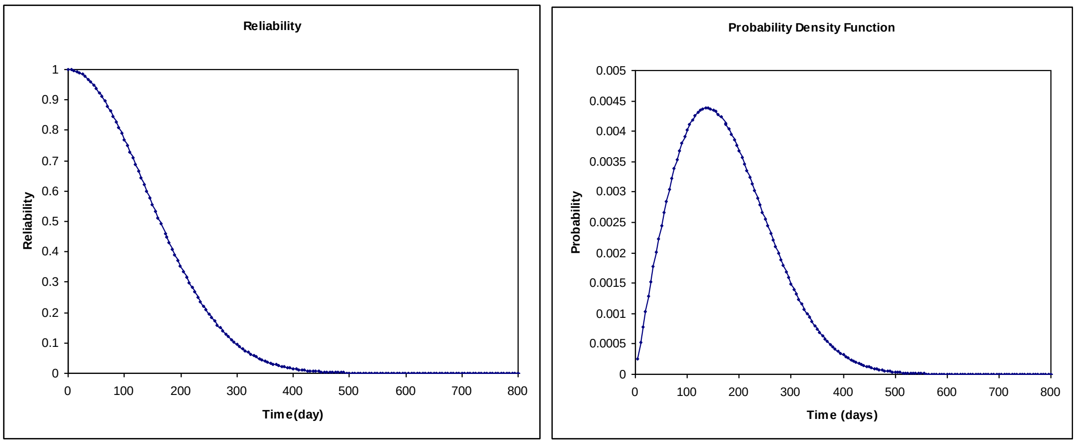
Maintenance Policy	Annual Cost (K$)	Cost Reduced (%)	Availability
No Preventive Overhaul	2421	Base	0.9726
Preventive Overhaul at MTBF	1960	19.04	0.9778
Overhaul at 80% MTBF	1848	23.67	0.9790

b) Probabilistic Approach

Using a probabilistic approach, the failures are represented by a probability distribution. The Reliability curve and Probability Density Function curve are shown in Fig.6. From this:

- The probability that the component will fail in 60 days is 10%.
- The probability that the component will fail in 120 days is 32%.
- The probability that the component will fail in 180 days is 57%.
- The probability that the component will fail in 300 days is 90%.

The component will fail most likely around 140 days, although MTBF is 178 days. This indicates that the component is more likely to fail after 140 days.



a) Reliability vs Time b) Probability Density Function

Fig.6 Reliability and Probability Density Function Curve

The frequency of preventive maintenance can be optimised based on economic data. The results of such an optimization are listed in Table.4. Optimum preventive interval is 105 days.

Table.4 Total Cost of Different Policy

Maintenance Policy	Annual Cost (K$)	Cost Reduced (%)	Availability
No Preventive Overhaul	2421	Base	0.9726
Preventive Overhaul at MTBF	1960	19.04	0.9778
Overhaul at 80% MTBF	1848	23.67	0.9790
Overhaul at Optimal Interval	1767	27.01	0.9800

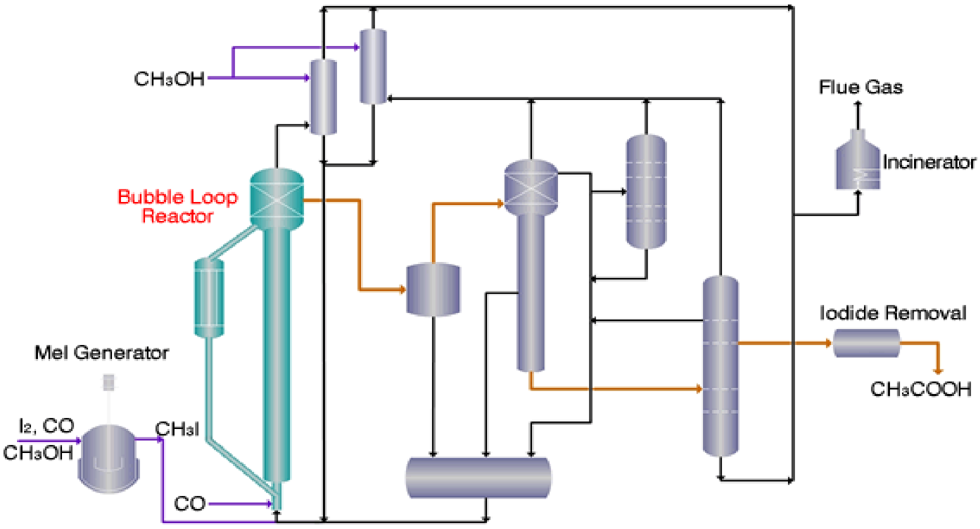
Cost optimisation using a probabilistic approach saves more money compared with the deterministic approach. Inappropriate preventive overhaul scheme can be avoided.

Redundancy Optimisation

Using standby components (sometimes referred to as spare or redundant components) is a common way to increase system availability and profit in the design stage, or even in retrofit. In addition to the inclusion of standby equipment, the standby equipment can be exploited in different ways. Instead of having one item of equipment on line and vulnerable to breakdown, there may be two, with one on-line and one off-line. But these two items of equipment can be sized and operated in many ways:

- 2 x 100% one on-line, one off-line switched off
- 2 x 100% one on-line, one off-line idling
- 2 x 50% both on-line, with system capacity reduced to 50% if one fails
- 2 x 75% both on-line operating at 2/3 capacity when both operating, but with system capacity 75% if one fails
- Etc., etc.

Since different units have different availability features and capital costs, engineers usually face difficulties to identify the optimum process structure – which unit should have redundancy, how many standby items are required, what is their capacity and what is their operating policy? Many factors should be considered when making decisions, e.g. availability target, investment budget, etc. Engineers need a systematic way to make decisions. Combining reliability analysis with optimization allows redundancy to be optimised with different objectives and constraints.



$$CH_3OH + CO \xrightarrow[CH_3I]{Rh/Resin} CH_3COOH$$

Fig.7 Process of Acetic Acid Production

Using Fig.7 as an example, standby pumps are required for the acetic acid production process. Pump data are listed in Table 5. Fig.8 and Fig.9 show two different designs. Fig.8 is to minimise the total capital cost with the availability target as 0.97. Pump D and Pump J are 2x50%, Pump E and G do not have standby, all the others are 2x100%. Fig.9 maximises system usage within a capital budget of 3.6x10^4 K$. Pump C does not have standby; all other pumps are 2x100%.

A mathematical tool can help engineers make the best decisions on a sound basis.

Table.5 Basic Information of Pumps

Pump ID	Capacity (%)	MTBF (operation) (days)	MTBF (standby) (days)	MTTR (days)	Availability	Capital Cost (K$)
Pump A	100%	300	4000	4	0.9868	320
Pump B	100%	300	4000	5	0.9836	628
Pump C	100%	200	2000	10	0.9524	8000
Pump D1	100%	220	4000	10	0.9565	4660
Pump D2	75%	220	4000	8	0.9649	4200
Pump D3	50%	250	4000	8	0.9690	3600
Pump E	100%	330	4000	4	0.9880	1116
Pump F	100%	280	4000	5	0.9825	176
Pump G	100%	300	4000	4	0.9868	1316
Pump H	100%	290	4000	4	0.9864	676
Pump I	100%	300	4000	4	0.9868	820
Pump J1	100%	310	4000	4	0.9873	504
Pump J2	75%	330	4000	4	0.9880	450
Pump J3	50%	350	4000	4	0.9887	390

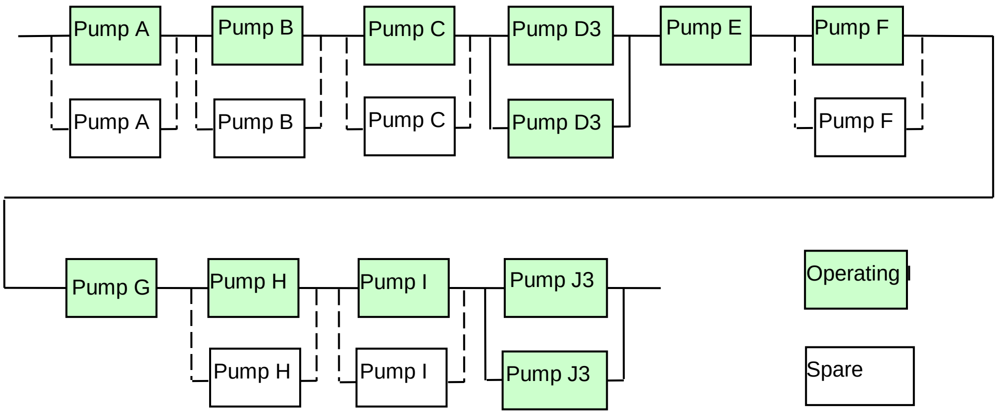


Fig.8 Minimise Capital Cost with Availability Target

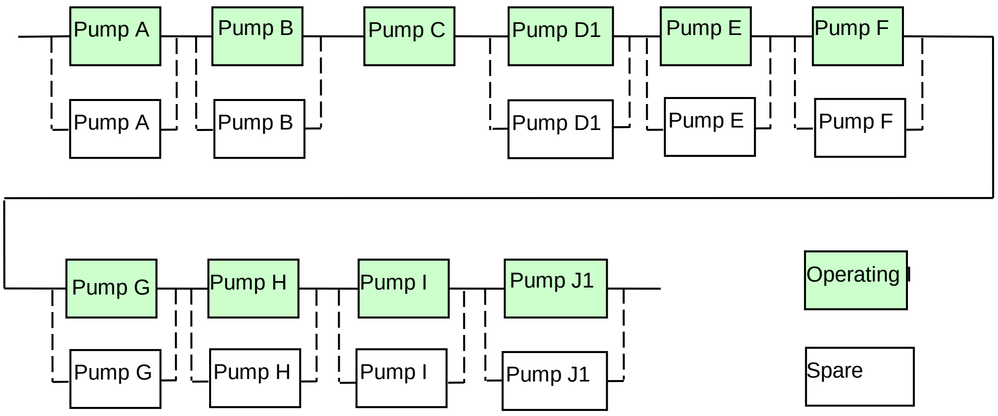


Fig.9 Maximise Usage within Capital Cost Budget

Preventive Maintenance Interval and Inspection Interval Optimisation

As shown in Fig.10, the Preventive Maintenance (PM) interval or Inspection interval need to be optimised to balance the maintenance cost and downtime penalty cost. Too frequent PM will interrupt the process and increase the cost of lost production. Too few PM will lead to unnecessary equipment failure and excessive maintenance cost, in addition to the cost of lost production. The interval of PM needs to be optimized to give the lowest total cost.

Another approach is to monitor the condition of equipment in order to determine the maintenance frequency. Many techniques are available, e.g. vibration monitoring. Such monitoring can be carried out continuously for critical equipment through on-line instrumentation, or off-line through inspection. If off-line condition monitoring is used, the frequency of inspection needs to be determined. Too frequent inspection brings unnecessary costs. Too infrequent inspection leads to unnecessary breakdowns. If components are maintained according to their condition, extra cost needs to be invested for the monitoring instruments. A systematic way is required to evaluate whether the investment is worthwhile or not, and help engineers to decide what policy should be used, real-time monitoring or inspection monitoring. The best inspection interval can be found by mathematical calculations with balanced maintenance cost, inspection cost, etc.

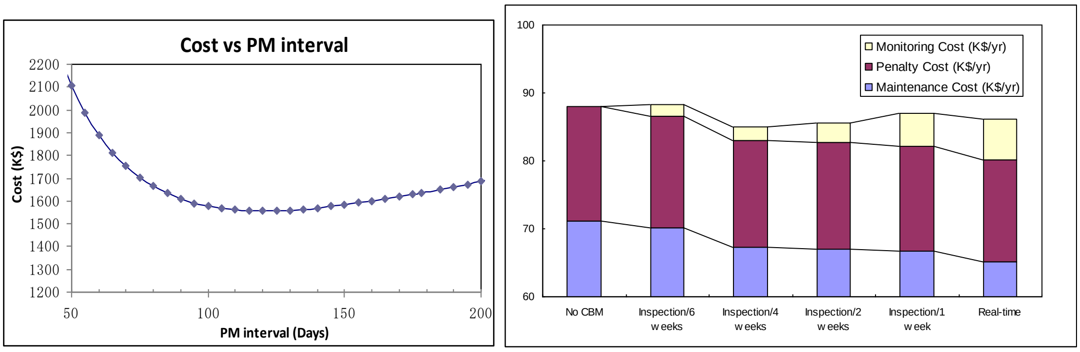


Fig.10 Cost vs PM Interval/ Inspection Interval

Spare Parts Optimisation

Spare parts need to be stocked in the warehouse in order that units can be repaired in time if they fail unexpectedly, or for planned maintenance. The holding cost and depreciation cost can be very high if too many parts are stocked. But if not enough parts are stocked, delivery delay time could increase system downtime and lead to extra penalty cost. Stocking policy should be determined according to the failure patterns of the parts. Mathematic analysis is necessary to find the best stocking policy and balance the stocking cost (including depreciation cost) and downtime penalty cost, as shown in Fig.11.

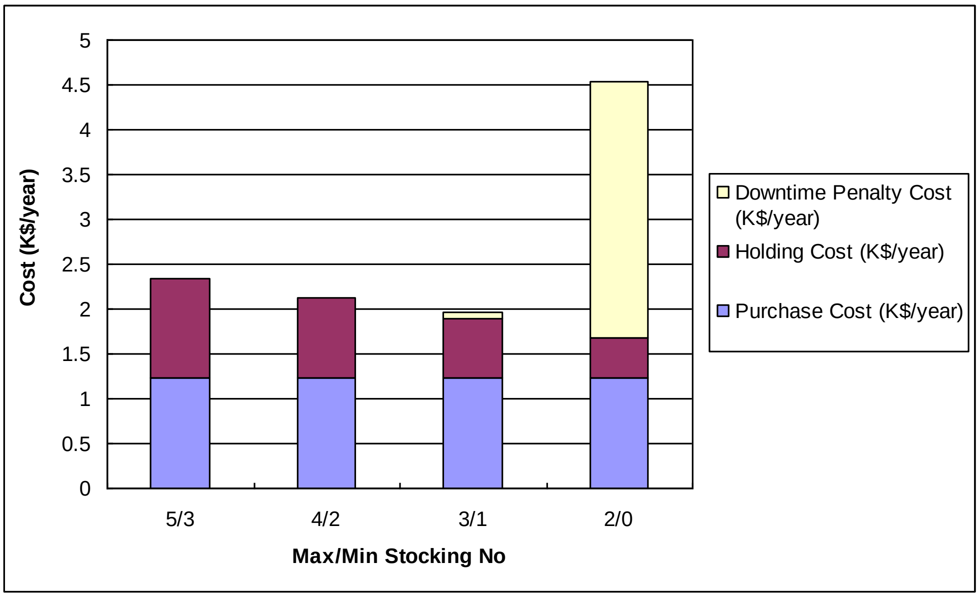


Fig.11 Total Cost vs. Different Stocking Policies

Methodology

Functions	Methodology
Data Regression	Rank Regression, Maximum Likelihood Estimation
RAM Simulation	Monte Carlo Simulation
Redundancy Optimisation	Markov Analysis with optimization
PM Optimisation	Monte Carlo Simulation with optimisation
CBM Optimisation	Monte Carlo Simulation with optimisation
Spare Parts Optimisation	Monte Carlo Simulation with optimisation