

## 04.4 RAM

A **design** function to model and predict reliability, availability, maintainability, operational costs, etc. of complex systems

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RAM analysis can predict performance of alternative system designs in terms of:

1. Mean Time Between Failure (MTBF);
2. Expected down time (Availability);
3. Expected repair and maintenance costs;
4. Expected spares usage;
- 5....

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RAM analysis uses Monte Carlo Simulation (MCS)

MCS is “working backwards” Start with F(t) and find t.

–Assume a component’s failure and repair distributions respectively are:

Failure age distribution

$F(t)=1-e^{-\left(\frac{t}{1600}\right)^{3.2}}$

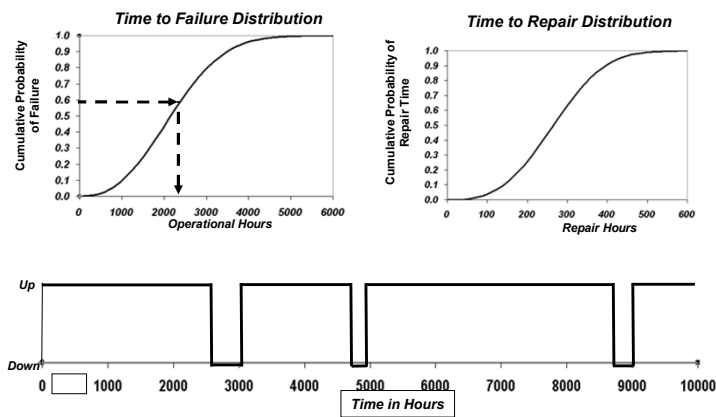
Repair time distribution

$F(t)=\text{Lognormal}\{\mu = \ln(6.2), \sigma = \ln(1.6)\}$

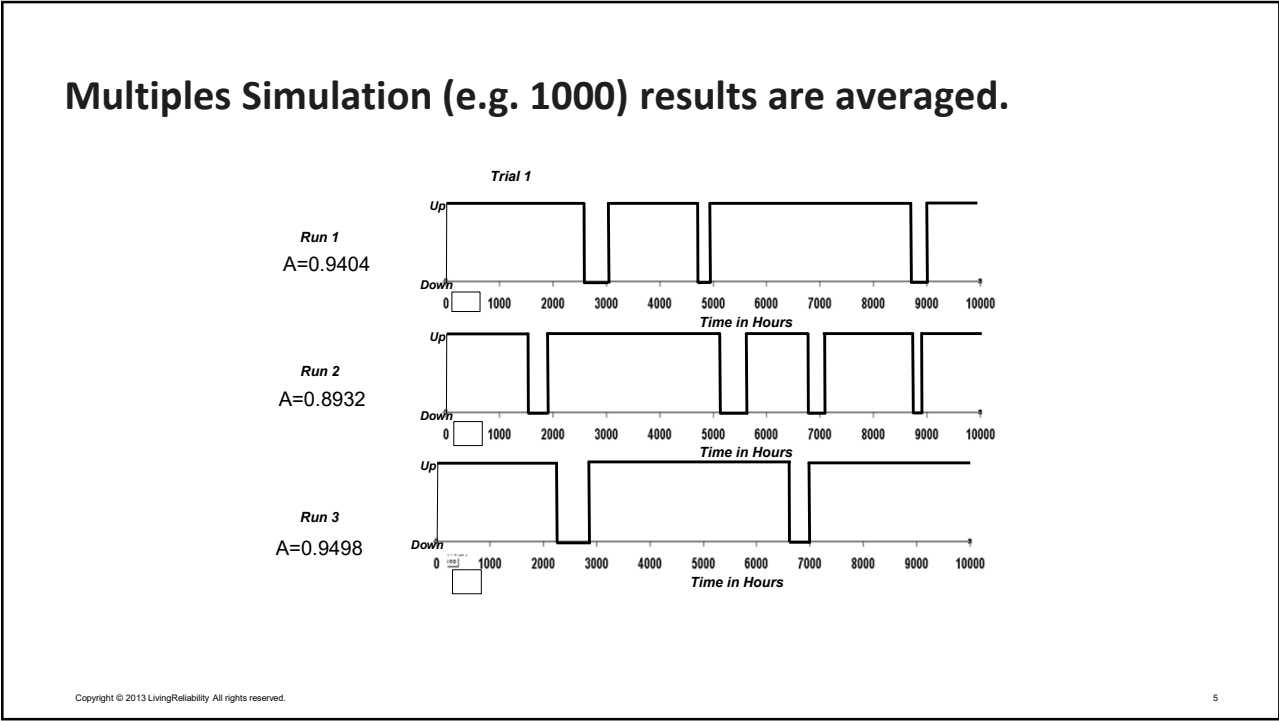
- For both distributions:
- 1.Let F(t) be a random number (from 0 to 1)
  - 2.Solve for t.

3

Simulation of a single mission of 10000 hours



4



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### Complex example 3 – a complex system

Problem statement

- Five cooling water pumps.
- Required: four pumps to be running.
- Net revenue from product sales: \$250,000/day
- Repair times for all pumps:  $\text{lognormal}\{\mu=600, \sigma=25\}$
- Average hourly repair cost for all pumps: \$150/hr
- Failure times for four pumps:  $\text{Weibull}\{\beta=0.8, \eta=24350\text{hours}\}$
- Failure time for fifth (older) pump: Unknown, but failures occurred on 11/13/91, 4/2/94, 8/19/95, 10/20/97, and 1/3/99
- Cost of a sixth pump: \$500,000 less 20% since existing auxiliaries can be used.
- Projected usage: 20 years ( $20 \times 365 \times 24 = 175200$  hours)

Is an upgrade justified? Compare the options: Status quo, replace older pump, add a sixth pump.

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Failure times of the fifth pump

	Days	Hours
13-Nov-91		
2-Apr-94	871	20904
19-Aug-95	504	12096
20-Oct-97	793	19032
3-Jan-99	440	10560

Fit failure times to a Weibull model

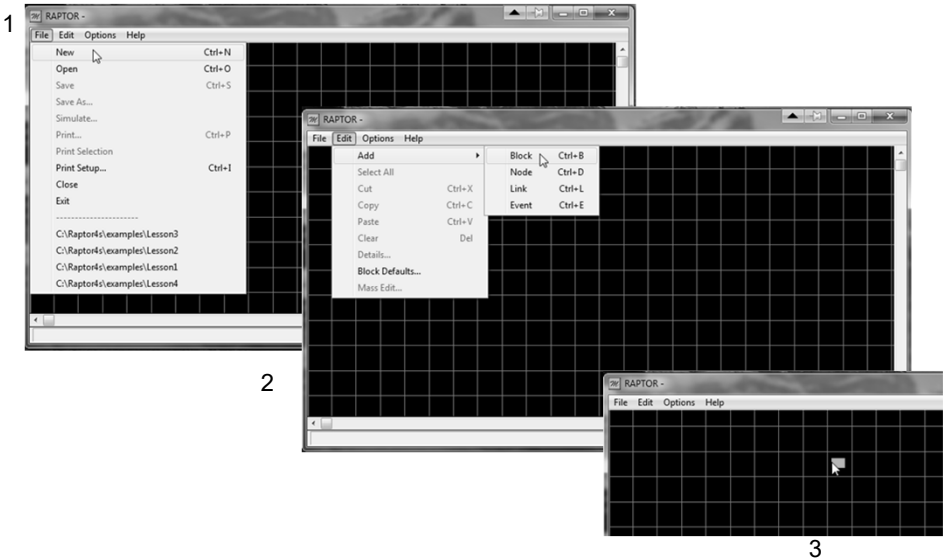
OREST - Data Input				
Components		Event Data		Operating Cost
Current Component				
Pump				
Event Data for the Current Component				
Record No.	Age	Frequency	Event Type	
1	20904	1	F	
2	12096	1	F	
3	19032	1	F	
4	10560	1	F	

Fitting Weibull Distribution		
Shape	3.17	
Scale	17457.46	
Location	0	

$F(t)=1-e^{-\left(\frac{t}{17457.46}\right)^{3.17}}$

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Set up the blocks and nodes for the status quo



8

### Set up the blocks for the 5 pumps

1

2

3

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Right click

Right click

Right click to remove this block

Change Pump1 to Pump2

Repeat these steps to create all 5 pumps

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### Change the properties of Pump5

Block Properties

General Failure and Repair Distributions Maintenance Information Advanced

FAILS

Shape Scale Location

Weibull 3.170000 17457.460000 0.000000

REPAIRS

Mean Standard Dev

Lognormal 600.000000 25.000000


Help Cancel Create Pool OK

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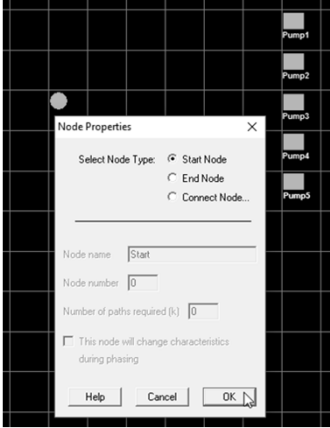
### Create a Start Node

1



The screenshot shows the RAPTOR software interface with a menu bar (File, Edit, Options, Help) and a toolbar. The 'Add' menu is open, and the 'Node' option is selected. The 'Node' submenu is also open, showing options like 'Block', 'Link', and 'Event'. The background shows a grid with several 'Pump' components labeled Pump1 through Pump5.

2

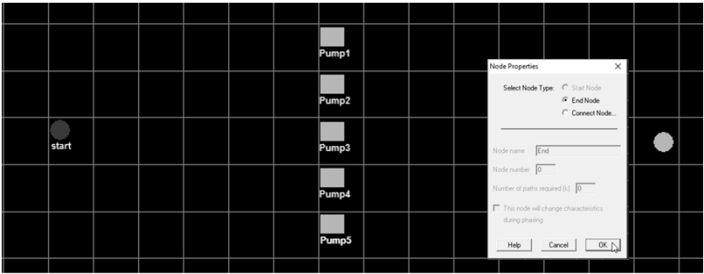


The screenshot shows the 'Node Properties' dialog box. The 'Select Node Type' section has 'Start Node' selected. The 'Node name' field is set to 'Start'. The 'Node number' field is set to '0'. The 'Number of paths required (k)' field is set to '0'. There is a checkbox for 'This node will change characteristics during phasing' which is unchecked. The 'OK' button is highlighted.

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### Create an End Node

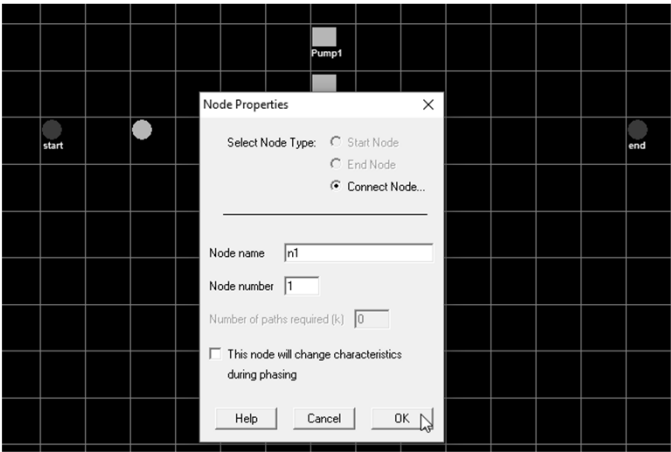


The screenshot shows the RAPTOR software interface with a grid containing a 'start' node and several 'Pump' components labeled Pump1 through Pump5. The 'Node Properties' dialog box is open, showing the 'EndNode' selected under 'Select Node Type'. The 'Node name' field is set to 'End'. The 'Node number' field is set to '0'. The 'Number of paths required (k)' field is set to '0'. There is a checkbox for 'This node will change characteristics during phasing' which is unchecked. The 'OK' button is highlighted.

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Create first Connect Node n1

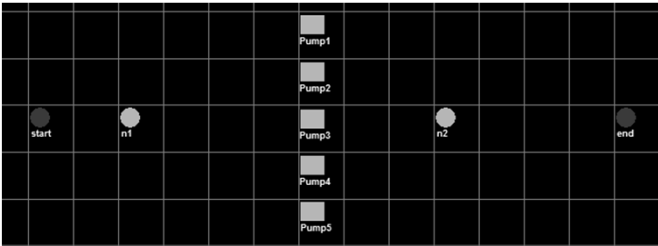


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Create second Connect Node n2



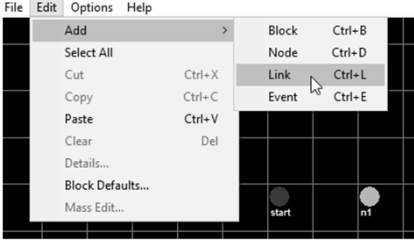
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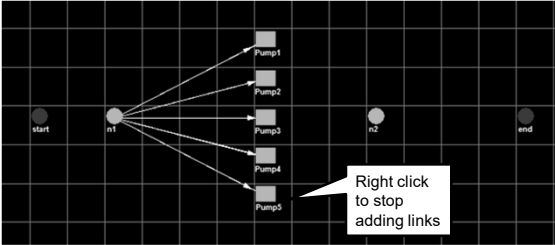
### Add links from n1 to all 5 pumps

1



The screenshot shows the 'Add' menu with options: Add, Select All, Cut, Copy, Paste, Clear, Details..., Block Defaults..., and Mass Edit.... The 'Link' option is highlighted, with a tooltip showing 'Link Ctrl+L'. Other options in the menu include Block (Ctrl+B), Node (Ctrl+D), and Event (Ctrl+E).

2



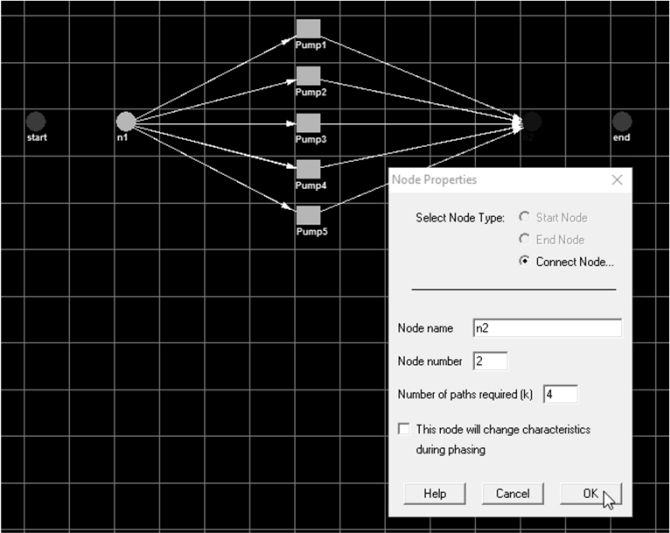
The screenshot shows a network diagram with a central node 'n1' connected to five pumps labeled 'Pump1' through 'Pump5'. A callout box points to the pumps with the text 'Right click to stop adding links'. The diagram also includes 'start' and 'end' nodes.

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### Add links to n2 and set Number of paths required to 4



The screenshot shows a network diagram with a central node 'n1' connected to five pumps labeled 'Pump1' through 'Pump5'. These pumps are then connected to a node 'n2'. A 'Node Properties' dialog box is open, showing settings for 'n2'. The dialog box has fields for 'Node name' (n2), 'Node number' (2), and 'Number of paths required (k)' (4). It also has a checkbox for 'This node will change characteristics during phasing' and buttons for 'Help', 'Cancel', and 'OK'.

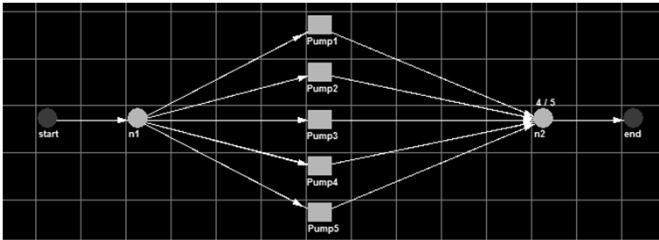
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Add Start and End links

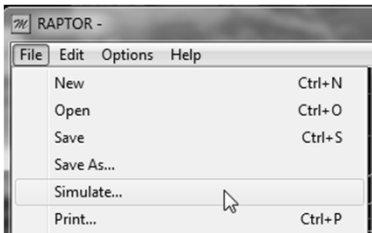


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Simulate the status quo scenario



Set up stop time and number mission time and number of runs

Stop simulation:

☒ At time

☐ At failure #

Number of runs

☒ Simulate with graphics

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View results

$Total\ Downtime\ Cost = (1 - 0.994541) \left[ \frac{\$250,000}{day} \right] \left[ \frac{365\ days}{year} \right] [20\ years] = \$10,019,250$

Results

Final Results

Results from 1000 run(s):

PARAMETER	MEAN	MIN	MAX	ST DEV
Ao	0.994540839	0.980712400	1.000000000	0.003590210
MTBDE	>78480.077970	17262.300506	>175200.000000	n/a
MDT (953 runs)	301.364244	0.387810	623.342932	111.755425
MTBM	4994.341124	3088.597044	8342.857143	865.343291
MRT	599.809985	583.243901	614.441341	4.444171
% Green Time	88.278598	81.934328	93.105903	1.866220
			6.812667	1.774405
			1.928760	0.359021
			10	1.934330

R(t=175200.000000)=0.047000

Average sparing data over 1000 run(s):

COMPONENT	START	END	MIN	MAX	# DELAYS
NOT USED					

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Simulate second scenario  
“replacing Pump 5”

Block Properties

General

Failure and Repair Distributions

Maintenance Information

Advanced

FAILS

Shape: Weibull

Scale: 3.170000

Location: 17457.460000

Change to 0.8

REPAIRS

Mean: Lognormal

Standard Dev: 600.000000

Change to 24350

Help

Cancel

Create Pool

OK

Simulate

Stop simulation:

At time: 175200.000000

At failure: 25

Number of runs: 1000

☒ Simulate with graphics

Results from 1000 run(s):

PARAMETER	MEAN	MIN	MAX	ST DEV
Ao	0.995402757	0.981245257	1.000000000	0.003420883
MTBDE	>90874.591548	19101.574341	>175200.000000	n/a
MDT (894 runs)	303.891418	4.033270	633.776237	116.072163
MTBM	5640.946651	2339.015184	13476.923077	1341.430825
MRT	599.745269	586.738000	614.263654	4.467037
% Green Time	89.367241	80.914602	95.638943	2.165359
% Yellow Time	10.173034	4.313959	18.059082	2.059328
% Red Time	0.459724	0.000000	1.875474	0.342088
System Failures	2.687000	0	9	1.825111

R(t=175200.000000)=0.106000

$Total\ Downtime\ Cost = (1 - 0.99541) \left[ \frac{\$250,000}{day} \right] \left[ \frac{365\ days}{year} \right] [20\ years] = \$8,395,000$

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Change Pump5 block properties

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### Simulate simulate 3rd scenario “adding a sixth pump”

RBD

Results from 1000 run(s)

PARAMETER	MEAN	MIN	MAX	ST DEV
Ao	0.999754621	0.992815904	1.000000000	0.000668225
MTBDE	>172095.325687	57980.448813	>175200.000000	n/a
MDT (109 runs)	196.160285	0.324723	591.633699	126.593982
MTBM	4238.628626	2576.479589	7963.636364	712.093652
MRT	599.354443	588.719779	612.040039	3.954049
% Green Time	96.334457	78.422430	92.605209	2.083991
% Yellow Time	13.641005	7.394791	21.577670	2.078994
% Red Time	0.024538	0.000000	0.718410	0.066823
System Failures	0.217000	0	3	0.481571
R(t)=175200.000000	>0.011000			

Total Downtime Cost = (1 - 0.999745)  $\left[ \frac{\$250,000}{\text{day}} \right] \left[ \frac{365 \text{ days}}{\text{year}} \right] [20 \text{ years}] = \$447,125$

Conclusions

	A	B	C	D	E
	Alternatives	20 yr. Avail.	Total Downtime Cost (\$M)	Initial Cost (\$M)	Total Cost (\$M)
5					
6	Existing System	0.99451	10.019	0	10.019
7	Replace older pump	0.9954	8.395	0.25	8.645
8	Add new pump to existing	0.999775	0.447	0.4	0.847

1. Best alternative: Add sixth pump.

2. This example shows how much impact even small improvements in system reliability can have.

3. Although the original availability, 0.99451 appears excellent, the example proves that it must be compared within an economic context to other alternatives.

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### Complex example 2

Problem statement:

A centrifugal condensate pump has components with the following Weibull failure distributions:

1. Mechanical seal ( $\beta = 0.75$ ,  $\eta = 967$  days)
2. Two bearings ( $\beta = 0.52$ ,  $\eta = 2701$  days)
3. Casing ( $\beta = 0.6$ ,  $\eta = 6095$  days)
4. Shaft ( $\beta = 0.43$ ,  $\eta = 7280$  days)

All repairs are lognormal ( $\mu = .5$  days,  $\sigma = 0.2$  days). What is the expected availability of the pump over a 10 year period?

Simulation

Stop simulation:

☒ At time

☐ At failure #

Number of runs

Results

Results from 1000 run(s):

PARAMETER	MEAN	MIN	MAX	ST DEV
Ao	0.998878691	0.996764151	1.000000000	0.000503693
MTBDE	>569.441640	158.182137	>3650.000000	n/a
MDT (997 runs)	0.493422	0.273079	1.003953	0.077120
MTBM	>569.441640	158.182137	>3650.000000	n/a
MRT (997 runs)	0.493373	0.273079	1.003953	0.077169
% Green Time	99.887869	99.676415	100.000000	0.050369
% Yellow Time	0.000000	0.000000	0.000000	0.000000
% Red Time	0.112131	0.000000	0.323585	0.050369
System Failures	8.304000	0	23	3.952687
R(t)=3650.000000	>0.003000			

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## 4.4.1 Quiz 1 RAM Analysis

<https://forms.gle/WsTCBdyhroEbVQEm8>

1. Which of the following statements are true about RAM? \*

1 point

- ☐ From an RCM perspective, RAM is not a form of maintenance, but rather of redesign
- ☐ RAM takes place in the conceptual design phase of a project to assist the owner with trade-offs between cost and capability..
- ☐ Maintenance engineers who do not perform RAM can still provide designers with useful data provided they have captured work order history consistently and accurately.
- ☐ RAM exposes the performance of various scenarios of interest.
- ☐ RAM uses the reliability and repair probability distributions taken from handbooks and from experience.
- ☐ All of the above.
- ☐ None of the above.

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