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Reliability Analysis of Centrifugal Pumps using Reliability Block Diagrams

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Abstract

Reliability Engineering uses a modelling approach specifically known as Reliability Block Diagrams (RBD) in order to evaluate all the characteristics of an asset during its life. The output of this exercise is a dynamic model illustrating different decision-making elements of the asset being studied. This includes economical aspects such as operating costs, spare part management, expected failures and other maintenance outcomes over time. This information allows and operator to correctly budget costs, logistics or labor requirements over the life of the asset. The model also allows the designer to estimate the production output of the asset over time and have a more realistic view of the design output. When it comes to preventive maintenance or redundancy (i.e. adding extra equipment), the model can be altered to visualize the expected output and incremental economical benefits or lack of there off, leading to better decision in terms of capital spending. The author will illustrate the study of a centrifugal pump and help the audience visualize all the above-mentioned aspects.

1 - Reliability Engineering theoretical concepts overview

Reliability in its academic root, is defined ***as the probability that a system will perform its intended function in a specified mission time and within specific process conditions***. The ***time*** variable is crucial in understanding the reliability of a system.

Reliability is calculated using historical records of a system or component. As shown below in Diagram 1 where “n” components are run on a test bench until they fail. Each failure is recorded and once all the failure records are collected, a normalized frequency graph can be constructed. This frequency graph helps define the statistical distribution that best represents the life cycle of each component in the population. Using specific mathematical transformations applied to the distribution, the probability of failure after any mission time can be derived as well as other information such as failure rate or the expected number of failures over time.

Hence, the derived statistical information can provide decision makers with key information about the operation of their assets such as:

- Is this probability of failure at a specific time acceptable?
- Given the consequence, is the “risk” acceptable?
- What can we do to make it better? Preventive maintenance, re-design, redundancy?
- Can the analysis give us more information on this component?

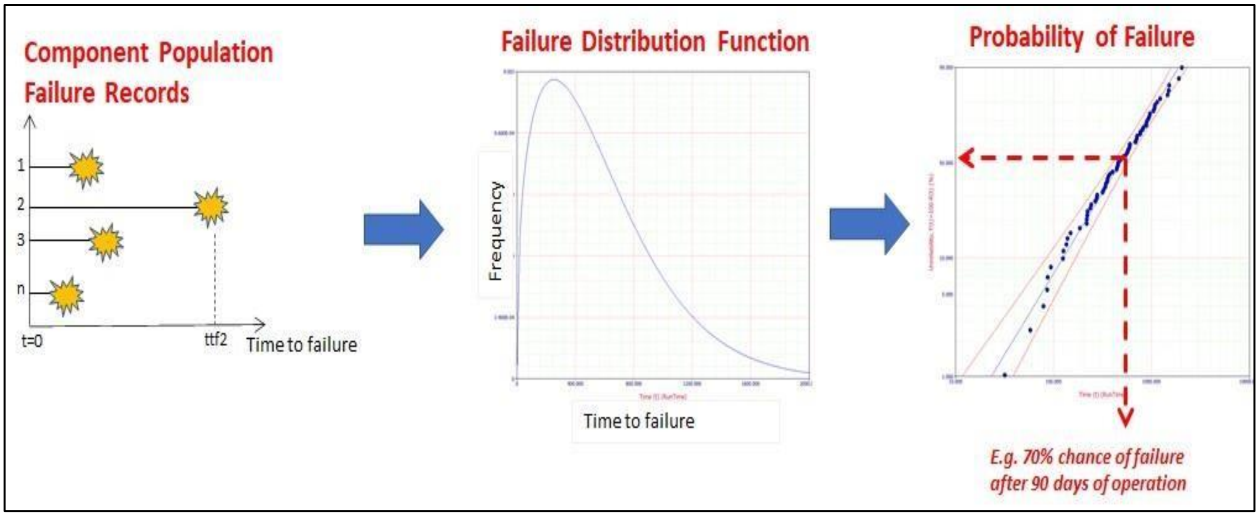


Diagram 1 – Theoretical overview of a Rreliability analysis

2 Introduction to Reliability Block Diagrams (RBDs)

The concept of Reliability Block Diagrams is also known as Reliability Modeling or Reliability, Availability, Maintainability (RAM) analysis. Using RBDs, interaction of large, complex and multi layered systems can then be analyzed using the Monte Carlo simulation methods (or Stochastic Discrete Event Simulation) hence quantifying the output of the entire system with greater accuracy than other estimating tools or methods.

In various industries, RBD models have proven their worth over time as an effective cost avoidance tool. As well as their ability to confirm or counter stated assumptions by internal stakeholders. Equipment upgrades and equipment sparing decisions are often seriously debated and costly decisions may not always be based on complete economical foundations but rather on avoiding past negative experiences or by following basic guidelines that are less than optimal. When a project or operational team needs to find an alternative, RBD is a tool of choice to evaluate, and justify the best option.

The fundamental purpose of RBD modeling is quantifying system performance. A system is a collection of items whose coordinated operation leads to the proper functioning of the system. The collection of items includes subsystems, components, software, human operations, etc. In RBDs, it is crucial to account for relationships between items to determine the reliability, availability and maintainability of the overall system.

The most common RBD arrangements are series and parallel systems illustrated in Diagram 2 below.

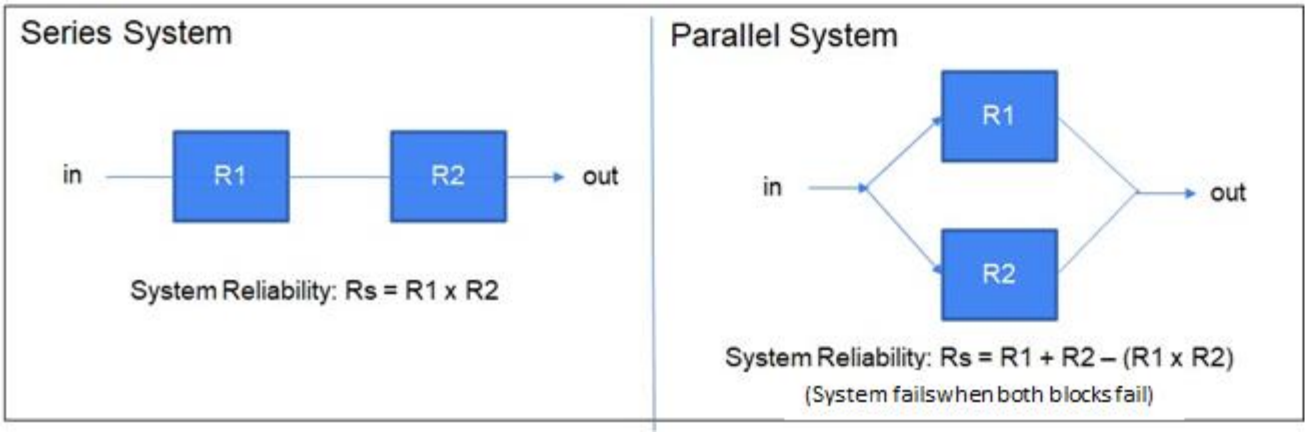
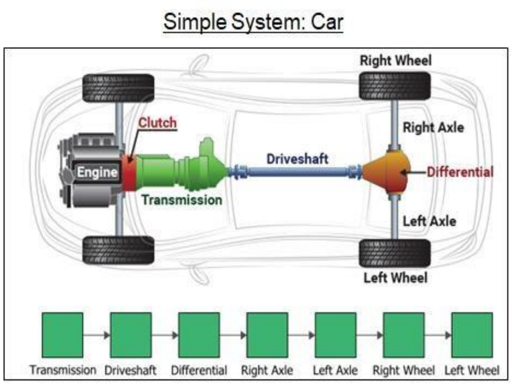


Diagram 2 – Illustrating basic RBDs and their reliability calculation equations

More complex RBDs are illustrated in Diagram 3 below. This also shows that this concept can be applied to highly integrated industrial systems such as refineries or pipeline networks going as far as space satellites.



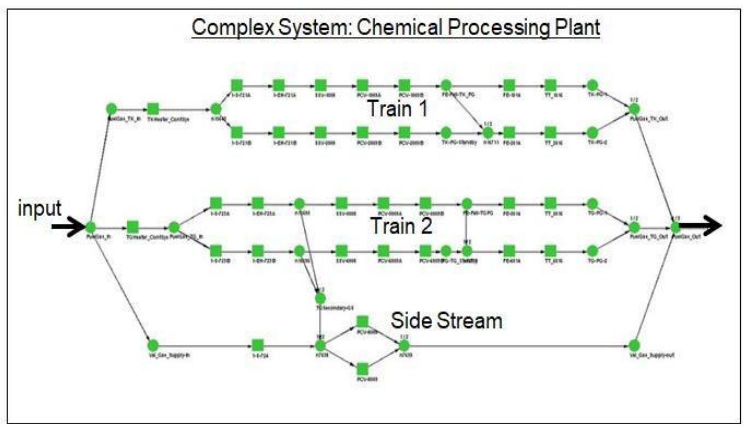


Diagram 3 – RBD examples for simple and complex systems

3 RBD applied to a centrifugal pump unit

In this section, the RBD concept is applied to a centrifugal pump. The pump itself is considered as the system and the first step is to find the significant components that influence the life cycle of this system. In other words, those components that fail regularly enough to have a significant impact on the performance of the pump as opposed to those that rarely fail. Diagram 4 below illustrates the "explosion" of the pump system into 6 significant components used in this example. An extra operational characteristic though not a physical component, is taken into account, i.e. trips or equipment lockouts. These are mainly operational interrupts triggered by the pump control system during abnormal operating conditions.

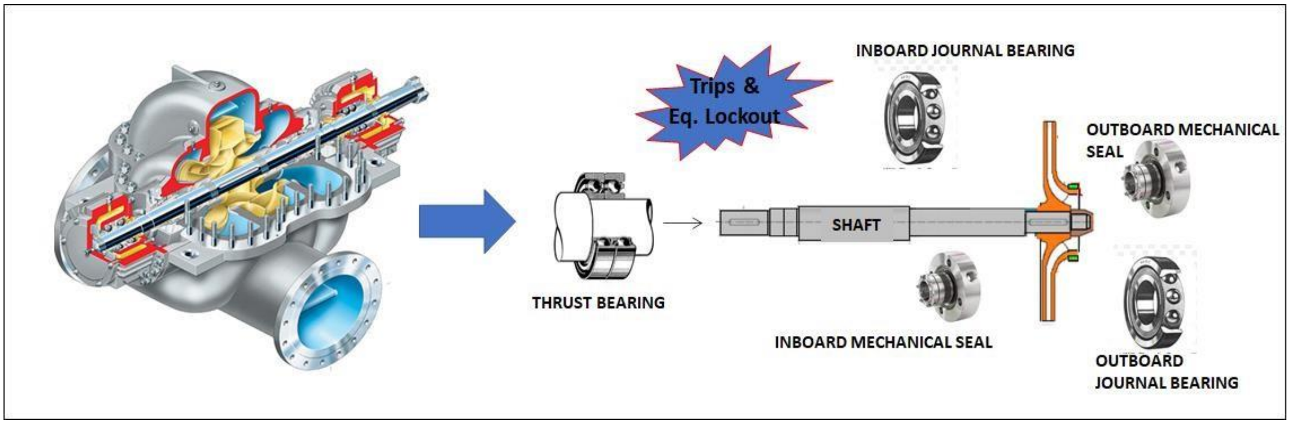


Diagram 4 – Illustration of centrifugal pump broken down into significant components

In terms of RBDs per se, the layout of the pump system and its components is a series configuration as shown in Diagram 5 below. The failure of any of the 7 blocks leads to the failure of the entire system.

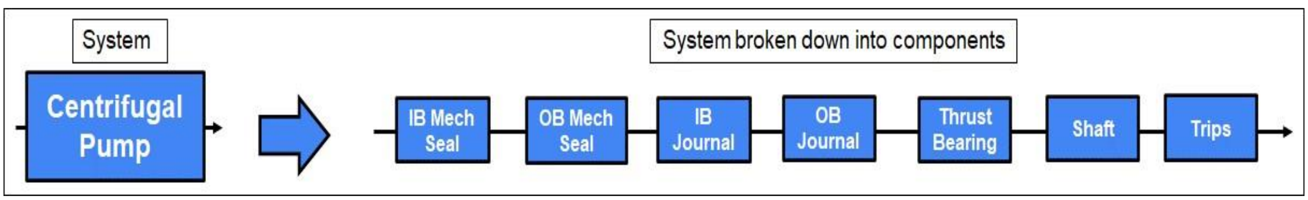


Diagram 5 – Pump system in a series configuration

3.1 RBD Inputs: Pump Life Characteristics

The RBD model required inputs such as life characteristics as well operational setups in order to simulate future performance. All the data provided in this paper is selected for the purpose of the example and not related to any proprietary system. They are, however, carefully selected to represent meaningful and realistic characteristics of a typical centrifugal pump.

3.1.1 Failure distributions

The failure distributions defined are based on the calendar time variable and illustrated in Diagram 6 below. Five failure distributions follow a Weibull distribution as well as an ageing failure pattern (shape parameter/Beta>1). This is in line with mechanical systems that age over time. The 6th distribution relating to Trips is an Exponential one indicating the randomness of those events mainly caused by external factors.

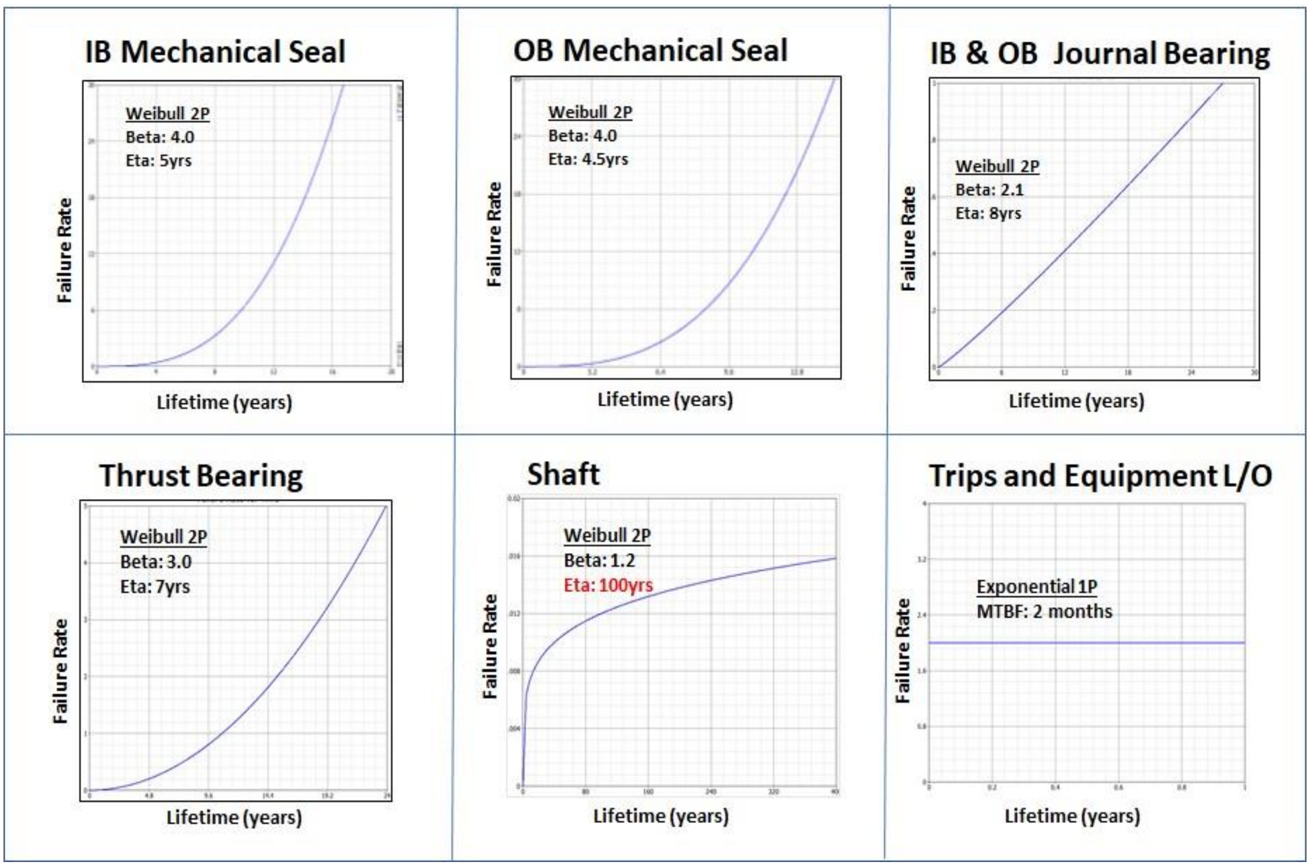


Diagram 6 – Component failure distribution and parameters

3.1.2 Repair and Preventive Maintenance distributions

The repair distribution or rather single point distributions as well as associated costs are provided in Table 1 below. Single values have been used solely for simplicity. In the real world, a specific distribution for repairs time (typically a log normal one) would apply.

	IB Mech Seal	OB Mech Seal	IB/OB Journal Brg	Thrust Brg	Shaft	Trips
Repair duration	8 hours	8 hours	8 hours	8 hours	48 hours	1 hour (reset)
Repair cost including Spare	$ 20,000.00	$ 20,000.00	$ 5,000.00	$ 7,000.00	$ 150,000.00	$ 200.00

Table 1 – Repair times and costs

There is only one PM attributed the whole pump system. It occurs every 3 months, takes 4 hours to complete and costs $500.

3.2 RBD Inputs: Pump Operational Characteristics

The pump operational characteristics are as follows:

- The pump is newly commissioned (i.e. start operating at time zero)
- As mentioned earlier, the time variable is calendar time indicating that the pump is expected to run continuously
- Pump throughput is 300 cubic meter per hour (m3/hr)
- Downtime cost is 1,000$/hour
- Gross revenue per cubic meter is $1.00

In order to maintain simplicity of the analysis other exclusions are made as follows:

- Spares are readily available without any wait time
- No Emergency spares (in case of stock depletion)
- No Spare Part Logistics cost
- No Spare Part Holding cost
- No Breakdown between labor, spares, and repair costs
- No utilities cost per hour of run time

3.3 RBD Outputs and results

3.3.1 Single pump simulation

The single pump RBD is as follows as illustrated in Reliasoft BlockSim™ which is the software used for this analysis.

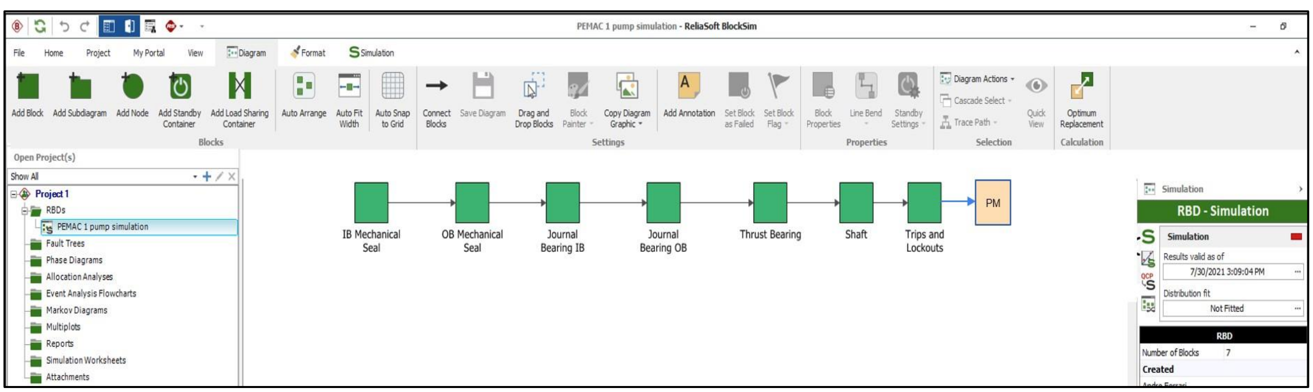


Diagram 7 – Pump System RBD as illustrated in Blocksim™.

The simulation run for the pump is done for 10 years and 1,000 lifecycles. Increasing the lifecycles or number of simulations will take longer to process but may yield more accurate results. In other words, the more simulations we have, the more the result becomes "statistically accurate". The result of the simulation is provided in table 2 below.

10-year run @ 1,000 lifecycles →

SIMULATION RESULTS

- System Availability: 99.67%
- System Reliability: 0%
- Number of expected unplanned failures: 67.52
  - OB Mechanical Seal: 2.02
  - IB Mechanical Seal: 1.73
  - Journal Bearing IB: 1.00
  - Journal Bearing OB: 1.03
  - Thrust Bearing: 1.20
  - Shaft : 0.06
  - Trips and Lockouts: 60.48
- Unplanned downtime: 119.00 hours
- Operating Cost: $408,387 (inc Spares @ $104,673)
- Net Revenue: $25,789,183

Table 2 – Simulation results for a one pump system over 10 years

Some comments on Table 2 are as follows:

- System Reliability is nil because the system fails at least once. However, System Availability can still be considered as high.
- The operating cost other than spares is related to downtime costs
- Component failure counts can be used to plan for spare parts or spares budgeting.

3.3.2 Opportunities for improvement

Table 3 below provides the details on operating costs and their relative proportions as part of the RBD simulation detailed output.

Block Name / Maintenance Event	Cost of Event	% Total Cost of Events	Number of Events
PUMP PM	$175,403.42	43%	38.99
Trips and Lockouts	$72,574.74	18%	60.48
OB Mechanical Seal	$56,499.14	14%	2.02
IB Mechanical Seal	$48,384.00	12%	1.73
Thrust Bearing	$18,000.00	4%	1.20
Journal Bearing OB	$13,442.00	3%	1.03
Journal Bearing IB	$12,995.87	3%	1.00
Shaft	$11,088.00	3%	0.06

Table 3 - Operating costs breakdown and proportions

Based on Table 2 and 3 above and in order to increase revenue by reducing downtime and operating costs, 2 improvement strategies can be considered as follows.

3.3.2.1 Improvement Strategy #1

According to both Tables 2 and 3, the high proportion of Trips is causing lost opportunities amounting to $72,575 or 90% (i.e. 60.48/67.52) of unplanned events. A Root Cause Analysis is suggested to find the cause and mitigate the high number of trips. Running the simulation with trip frequency reduced to 1 per year (down from 1 every two months) we get a revenue increase of $15,042 over 10 years. This saving could in essence justify conducting an RCA.

3.3.2.2 Improvement Strategy #2

Table 2 shows that PMs account for 43% of the operating costs. The current operation has a high frequency of PMs but still a high number of unplanned failures suggesting that the PM program may be ineffective yet costly. The improvement strategy would hence be introducing a PM program based on the **Optimal Replacement Time** technique. This technique involves preventive replacement of assets at specific interval defined by the RBD simulation (Reference 2).

The Optimum Replacement Time replacement technique has 3 different possibilities

1. Preventive replacement for individual components at different intervals
2. Preventive replacement for individual components at the same intervals (i.e. all replaced at the same time a bit like an overhaul)
3. Preventive replacement for individual components at different intervals based on inspection results (a.k.a. on-condition inspection). In other words, on condition inspections are conducted at specified intervals and depending on the deterioration observed, preventive replacement is conducted or not. This is also based on a "detectability level" of deterioration in the component under inspection.

Since, the above 3 techniques involve preventive work, the cost of replacement will be lower than the cost associated with unplanned work. This is illustrated in the following 3 tables. Additionally, it can be noticed the there is no optimum replacement time associated with shafts due to the nature of its life cycle characteristics.

Block Name	Planned Replacement Cost	Unplanned Replacement Cost	Optimum Replacement Time (yr)
OB Mechanical Seal	$ 15,000.00	$ 24,500.54	3.88
IB Mechanical Seal	$ 15,000.00	$ 24,501.90	4.31
Journal Bearing IB	$ 2,000.00	$ 9,499.57	4.15
Journal Bearing OB	$ 2,000.00	$ 9,501.90	4.15
Thrust Bearing	$ 3,000.00	$ 11,501.90	3.96

Table 4 - Component Replacement at DIFFERENT intervals

Block Name	Planned Replacement Cost	Unplanned Replacement Cost	Optimum Replacement Time (yr)
OB Mechanical Seal	$ 15,000.00	$ 24,500.54	4.08
IB Mechanical Seal	$ 15,000.00	$ 24,501.90	4.08
Journal Bearing IB	$ 2,000.00	$ 9,499.57	4.08
Journal Bearing OB	$ 2,000.00	$ 9,501.90	4.08
Thrust Bearing	$ 3,000.00	$ 11,501.90	4.08

Table 5 - Component Replacement at IDENTICAL intervals

Block Name	Planned Replacement Cost	Unplanned Replacement Cost	Inspection Cost	Deterioration Detection Ability	Optimum Inspection Time (yr)	Replacement
OB Mechanical Seal	$ 15,000.00	$ 24,500.54	$ 500.00	75%	1.30	if 80% of life achieved
IB Mechanical Seal	$ 15,000.00	$ 24,501.90	$ 500.00	75%	1.44	if 80% of life achieved
Journal Bearing IB	$ 2,000.00	$ 9,499.57	$ 100.00	90%	0.49	if 90% of life achieved
Journal Bearing OB	$ 2,000.00	$ 9,501.90	$ 100.00	90%	0.49	if 90% of life achieved
Thrust Bearing	$ 3,000.00	$ 11,501.90	$ 100.00	90%	1.26	if 90% of life achieved

Table 6 - Optimal Inspection intervals followed by Conditioned Based replacement

Using those 3 preventive replacement strategies as well as a hybrid of the techniques 2 and 3 highlighted above, RBD simulations are run for 10 years. In addition, the two following criteria are applied:

- PM tasks are reduced in terms of frequency from 3-monthly to yearly.
- The Trip/Equipment Lockout distribution has not been changed and remains the same as originally defined section 3.1.1. The reason for this is to specifically show the effects of the new preventive replacement tasks on the operation.

Table 7 and 8 below summarize the results for each of the 5 operating scenarios including the 1st case.

Based on those 2 graphs, it appears that the highest net revenue generation is with preventive replacement strategy S2. This option is not necessarily the one with the lowest number of failures which suggests that spending more resources on preventive tasks may not always be cost effective and should be carefully assessed using RBD simulations.

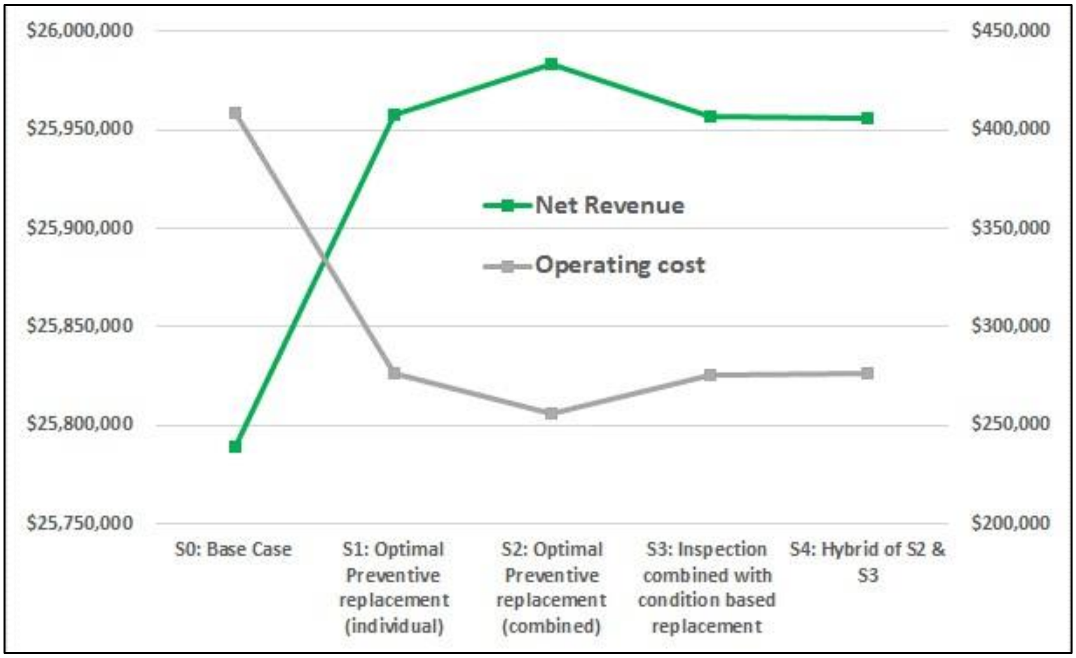


Table 7 - Net Revenue and Operating Cost for each strategy

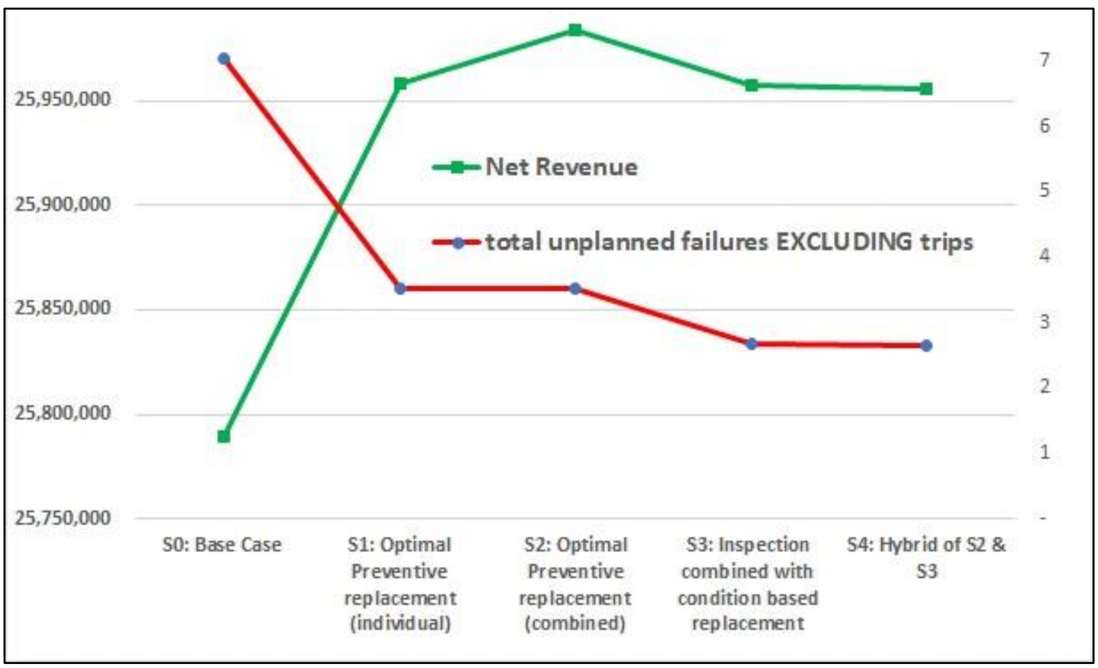


Table 8 – Unplanned failures (excluding trips) and net revenue for each strategy

3.3.3 Multiple Pump RBDs – Concept of Redundancy

The above example of a single pump system running on its own is not the true reality in an operating environment. In order to maintain reliability and availability, equipment such as pumps are typically set up in multiple numbers or with redundancy. This means that if an individual pump fails, the other pump in standby can take over more or less immediately depending on the controls setup, and in doing so, maintain flow. Using option S0, two identical pumps are placed in a parallel arrangement as shown in Diagram 8 below. The operational characteristics of the system are as follows:

- 1 out of 2 pumps is needed to maintain production
- The second pump is a warm standby meaning that it starts immediately when the other one stops but obviously only if it is in running condition (i.e. not down for repairs).

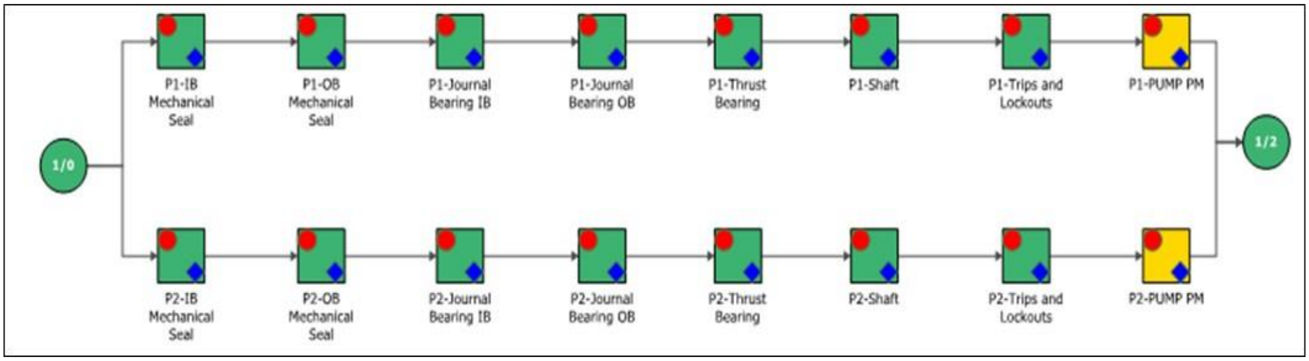


Diagram 8 – 2 pump system in parallel arrangement and warm standby for non-operating pump

The results of a 10-year simulation run are shown in Table 9 below.

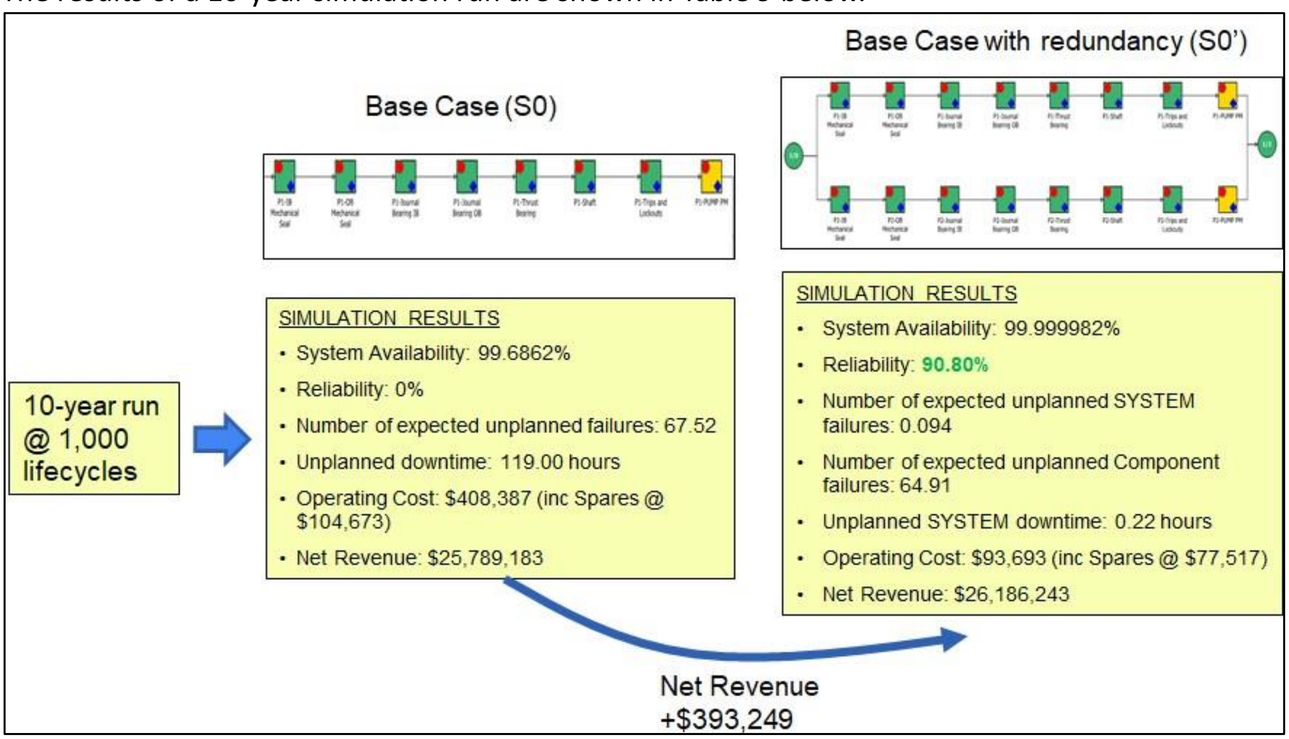


Table 9 – Simulation results for a TWO pump system over 10 years

The result of this last simulation from one to two pumps in a standby mode clearly shows an increase in reliability, availability and net revenue amongst other improved metrics. However, redundancy does come at a cost and should also be economically justified. This will be demonstrated in the next example.

3.3.4 Capital cost investment evaluation using RBDs

This example involves evaluating whether a third pump is economically justified based on periodic increases in throughput hitting a 2 pump system's capacity limits. RBDs allow simulation of periodic changes in production values and this is known as phasing. The operational characteristics of the system are as follows:

- The current pump arrangement is two standby pumps at 200m3/hr capacity each
- The phasing or alternating throughput changes are
- 2 months at 400m3/hr with a 2 out of 2 pump requirement
- 10 months at 200m3/hr with a 1 out of 2 pump requirement
- The cost of an extra identical pump is $500,000 fully installed and operational
- All pump components and maintenance setups are based on the base case scenario (S0).

Intuitively due to reliability issues, maximum capacity at 400m3/hr can be achieved but due to the lack of redundancy in a two-pump system, there will be system downtime and revenue losses since two pumps can be down at the same time when both are required to run. Hence why a 3rd pump should be considered. Diagram 9 below illustrates the 3 operating scenarios considered including with and without phasing.

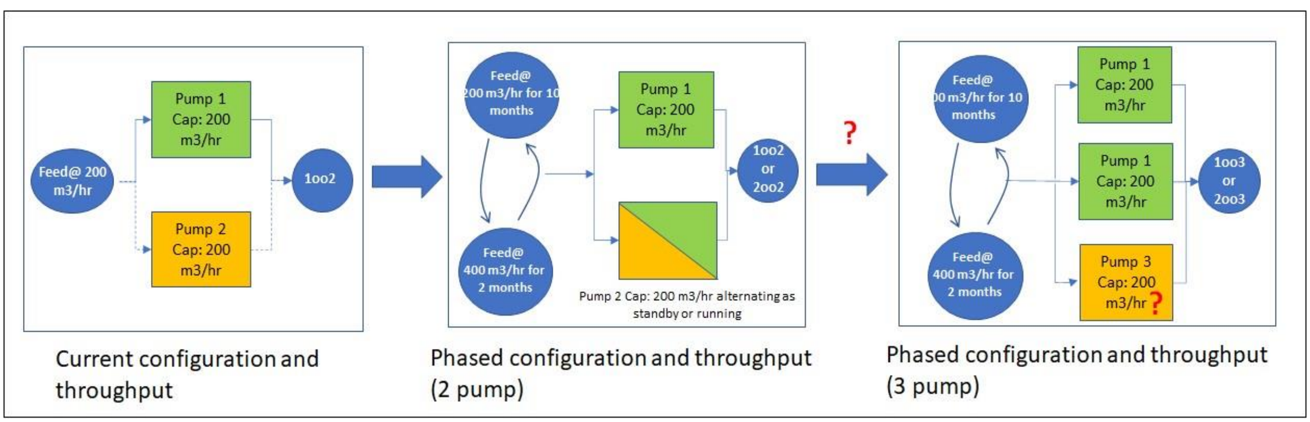


Diagram 8 – 3 options considered in the pump addition justification

The simulation is now run for 30 years because this is the expected lifetime of a typical pump. Table 10 below provides the comparative results for the 3 options.

Case	2 pump configuration and throughput without phasing	Phased configuration and throughput (2 pump)	Phased configuration and throughput (3 pump)
Availability	99.9999%	99.9461%	100.0000%
Reliability	80.00%	0.00%	86.70%
Net Revenue	$ 52,375,183	$ 60,898,998	$ 61,102,875
Net Revenue Increment		$ 8,523,815	$ 203,877

Table 10 – Simulation results for 30 years showing incremental net revenue

Table 10 indicates that a 3rd pump is not justified mainly because the incremental revenue is lower than the cost of the new pump. This is the case even if availability is at 100% and reliability has significantly increased.

Conclusion

This paper highlights the overall benefits of using RBDs in decision making processes involving capital cost, design, maintenance strategies and spare parts budgeting. The examples used are simplified for the purpose of understanding this analytical technique but can be made more complex and pertinent to the operation itself. Using RBDs in the design phase can save a project significant amounts of capital expense let alone future issues leading to lower reliability or availability. RBDs can also be used effectively to assess the performance of an operation even years after commissioning. Finally, building RDBs in an operation leads to increased collaboration within teams as the inputs and also outputs span a wide variety of specialties and organizational needs.