The effect of combining reliability, availability and maintainability modelling and stochastic simulation modelling on production efficiency

FJ van der Weshuizen

orcid.org 0000-0002-0836-0639

Thesis accepted in fulfilment of the requirements for the degree
Doctor of Philosophy in Operational Research
at the North-West University

Promoter: Prof PD Pretorius

Graduation: April 2019

Student number: 12375322

ACKNOWLEDGEMENTS

Doing this doctoral work and thesis was undoubtable, the most demanding task I have undertaken. However, one of the joys of having completed the thesis is looking back at everyone who has helped me.

Praise and thanks to the Almighty God, Jesus Christ, who made all possible, no words can describe my gratitude. Your grace is enough. “I can do all things through Christ who strengthens me.” *Philippians 4:13*

Second, I would like to thank my supervisor Professor Philip Pretorius for his guidance, reading every line of my thesis, and that one phone call to motivate me to continue.

To my family, particularly my parents and brother, thank you. Without you, I would not be the person I am today. The shape of me lies in your hands.

I would also like to thank the following people for their input: Marlize Meyer, Prenitha Pooren, Preston Ferreira and Diki Langley.

Milée and Lika, I need to apologise for time I have lost with you while doing this. I hope one day you will understand why I did this and that it inspires you to never give up.

Also, I would like to thank Sasol who applies a wide range of Operations Research (OR) techniques and for giving me this opportunity to add value.

Above all, I would like to thank my wife, for all the weekends, late evenings and early mornings I sat in front of the computer while you were running the household, and for keeping me sane over the last few years. Thank you for being my muse and sounding board. But most of all, thank you for being my best friend. I owe you everything.

Finally, despite my love for data science, this study would not have been possible without the financial support of Sasol and the North-West University.

“Keep your smile for your enemy, your tears for your friend, your heart for your fellow man, your judgment for yourself and your conscience for God” C.J. Langenhoven

ABSTRACT

Many world leaders in manufacturing are currently designing future facilities at various global locations. A Reliability, Availability and Maintainability (RAM) study is an important part of the basic engineering process. State-of-the-art RAM modelling, however, was not able to address the combined variability and complexity of oil and gas facilities.

An opportunity thus arose to use stochastic simulation in combination with RAM models to meet the challenge of determining the reliability and production efficiency of a facility. This approach also allowed new factors to be considered in the RAM analysis such as ramp-up/down rates, upstream and downstream upsets and storage.

RAM modelling identifies the critical equipment and systems that contribute to lost production and defines the frequency and duration of outages. The basis is a Reliability Block Diagram (RBD) with parallel and series equipment configurations. This deterministic calculation can be complemented by the use of a Monte Carlo simulation to assess stochastic factors. Neither of these techniques, either alone or in combination, was able to address the variability and complexity of a major value chain.

The combination of RAM and Stochastic models demonstrates best practice for process reliability modelling of manufacturing companies with complex value chains.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ARS	Applied Reliability Symposium
BBL	Barrels
BFD	Block Flow Diagram
BRAM	Benefit of Reliability, Availability and Maintainability
CM	Corrective Maintenance
DES	Discreet Event Simulation
EXP	Exponential Distribution
INFORMS	Institute for Operations Research and the Management Sciences
MTTF	Mean Time to Fail
MTTR	Mean Time to Repair
FN	Failure Number
NOR	Normal Distribution
OR	Operations Research
OREDA	Offshore Reliability Data
ORSSA	Operations Research Society of South Africa
PDF	Probability Density Function
PFD	Process Flow Diagram
PM	Preventative Maintenance
QOI	Quality of Interest
RAM	Reliability, Availability and Maintainability

RBD	Reliability Block Flow Diagram
SME	Subject Matter Expert
SOW	Scope of Work
SSE	Sum of Squared Errors
USD	United States Dollar
UPS	Un-Interruptible Power Supply

CHAPTER 1: INTRODUCTION

1.1 Background

The world of Operations Research (OR) is forever changing to a new and more critical function under the data science umbrella. More data, faster and cheaper computers, applications fit for purpose, easier accessibility to data science and data scientists and a world focus on analytics and optimisation are some of the reasons why businesses are moving towards more analytics, and in doing so expands OR in the world. Large scale problems has become the norm and this is particularly true for the oil, gas and chemical environments. Higher safety requirements, increased system reliability and a focus on predictive maintenance all plays a role in how these companies will prepare for the future. System reliability can efficiently be done when a Reliability, Availability and Maintainability (RAM) analysis is performed. These types of analysis help decision makers with design, effective sparing, and optimisation of complex systems (Jackson, et al., 2005).

A quantitative calculation is performed by analysing reliability data for value chains at entire system and subsystem level. The reliability of the components must be combined with accurate distributions for failure and repair times in the value chain to justify the investment required for sustainable operability and reliability of the system. RAM modelling of the value chain combines this information into a model, using Monte Carlo simulation (Hojjati & Noudehi, 2015).

This work yields an availability number considering the parallel and series nature of the components in the value chain, with fraction capacity to accommodate the time based impact on the value chain. In this study it shows the need to put more emphasis on modelling the hour to hour dynamics observed in the system. In petrochemical plant this means for example the ramp –up of equipment after a shutdown or failure, the cooling down of equipment before it can be opened, catalyst deterioration, impact of buffering and planned maintenance actions. This modelling is combined with the RAM to give a believable production throughput number that can be compared to the throughput observed in the operation unit, plant or value chain. Discrete-event simulation (DES) is the technique chosen for this study and in addition, the coordination and integration of DES simulation models provide a robust decision support tool (Meyer, et al., 2011).

Stochastic simulation uses the output from a completed RAM analysis as input to then model the production efficiency of a system. Combining these two simulation techniques has provided an innovative way to support decisions in a modern production facility. The RAM models can help to minimise downtime of existing facilities and supports decision-making on new facilities also providing a realistic throughput with the stochastic models for each scenarios (improvement alternative). The value of these models has been repeatedly shown through improvements to the bottom line for many business units and sites.

Figure 1, on the next page, illustrates the effect of RAM modelling and stochastic simulation modelling on production efficiency.

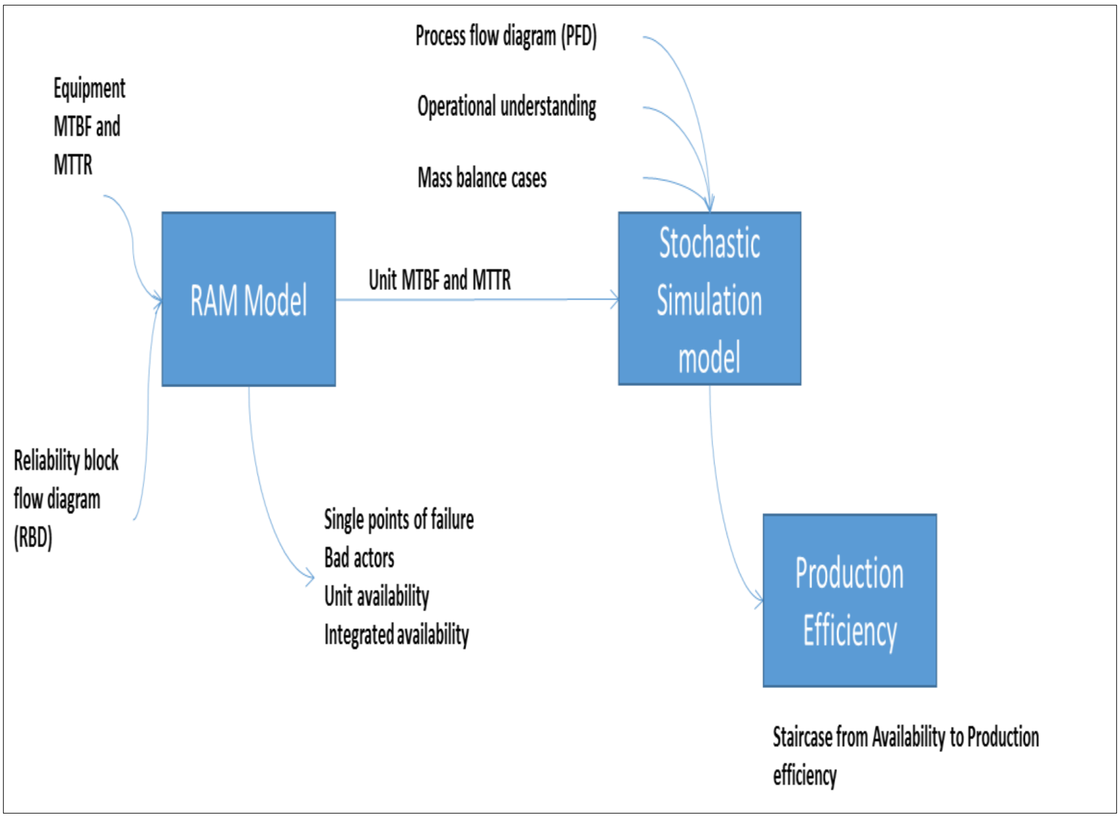


Figure 1: The effect of RAM modelling and Stochastic Simulation modelling on Production Efficiency

This thesis will explain that Production Efficiency can be calculated more accurately by a combination of RAM modelling and stochastic modelling.

This research study forms part of the OR field. It will contribute to the OR area by comparing and evaluating RAM modelling and stochastic modelling techniques. This study will justify the combined use of these techniques as a decision support tool to support management decisions. Its contribution to the interest group is an innovative combination of techniques shown through the analysis and modelling of data from a company's' facilities as well as various internationally accepted databases.

In this chapter, the background is reviewed in Section 1.1. There will be a general review of stochastic modelling in Section 1.2. RAM modelling gets discussed in Section 1.3 and the problem statement, the main research question and the hypothesis will be explained in Section 1.4, Section 1.5 and Section 1.6. Next, the method of investigation is in Section 1.7 and a detailed chapter outline in Section 1.8.

In Section 1.2 Stochastic simulation modelling is described.

1.2 **Stochastic simulation modelling**

The definition for stochastic simulation modelling is as follows: “A broad collection of methods and applications to mimic the behaviour of real systems, usually on a computer with appropriate software. In discrete-event simulation (DES), the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system” (Banks, 1998). Stochastic modelling will be used to calculate the volumetric impacts of a system or process and RAM modelling the impact of failures and repair times on the system.

1.2.1 Discrete event simulation (Using Arena®)

According to Kelton et al. (2005:12) "Rockwell Software’s Arena® combines the ease of use found in high level simulators with the flexibility of simulation languages, and even all the way down to general-purpose procedural languages like the Microsoft®, Visual Basic® or C®. It does this by providing alternative and interchangeable templates of graphical simulation modelling-and-analysis modules that you can combine to build a fairly wide variety of simulation models".

Arena® supports both continuous and discrete processes in a system and consequently also poses the competence to estimate continuous processes in a discrete way (Meyer, 2004).

Arena® is hierarchical and the actual model looks much like a flow diagram with different parts of the model being modelled as sub models if required. Arena® also has many animation features to show the progress of entities through the system (Kelton, et al., 2015).

An entity can be a part or a person or whatever needs to move in or through the system. Entities can also be essential, for example where an entity is used to change a variable in the system at specific points in time (Henry, et al., 2014).

Meyer (2004:11) states that the value of a variable in Arena® is global and similar to other programming software, and can be seen throughout the model. The characteristic of an entity belongs only to that entity and will be part of that entity as it progresses through the model.

“All the basic building blocks, advanced random number generation and sophisticated summary are provided in Arena®. Because of complexity of systems, Arena® has gone through a rigorous process to prove that the software are able and capable of handling complex systems (Meyer, et al., 2011).”

Section 1.3 is about RAM simulation modelling.

1.3 **RAM simulation modelling**

Similar to all other industrial regulations, reliability engineering uses highly concentrated terms with clear-cut meanings. However, many of these terms have different meanings to what is used elsewhere on a day-to-day basis; therefore, the description of terms used in the RAM field is of significance (Sutton, 2010).

1.3.1 Reliability

"The reliability of a component or of a system is the probability that it will perform a required function without failure under stated conditions for a stated period of time. (Calixto, 2016)*"*

Reliability is a fast growing discipline which aims to develop methods and tools to predict, evaluate and demonstrate better input into RAM models. The reliability of any system and component has become a crucial part in the design phase of any company. In the current competitive global economy environment, companies are forcing manufacturers to produce exceedingly reliable, safe and easily maintainable engineering products.

The definition of reliability lists the following circumstances where reliability should not be considered (Adhikary, et al., 2012):

- Reliability can describe the equipment in a system or to the sub-system. The current expression of availability has more to do with system analysis;

- A value associated likelihood is related to reliability; no equipment is assured to function or assured to break;
- The term required function also features in the above definition. All the equipment and systems are planned for a specific duty or arrays of duties. If a piece of equipment is required to achieve a result on a non-specified duty and then fails, the piece of equipment itself was not unreliable;
- In the same way, the stated conditions must be looked at very carefully. For example, if a piece of equipment is not operated in the design temperature range then failure of that piece of equipment does not mean that it was unreliable; and
- By definition, reliability speaks of only a certain entity of existence. Nothing is built to last forever; ultimately, everything has an end date. The number of simulation cycles could also refer to the beginning and the end of a system, sub-system, or piece of equipment.

1.3.2 Availability

The definition is as follows:

“The availability of a repairable system is the fraction of time that it is able to perform a required function under stated conditions. (Barlow & Proschan, 1975)*”*

The norm is that availability applies to systems and reliability to equipment within those systems. Reliability and availability are illustrated in the Figure below. Over a certain period, the value of availability averages out at a high percentage value (O'Connor, et al., 2002). For example, the availability of a facility could be at 98%; this would suggest that the facility is running at 98% of the time the organisation wants it to run. Individual pieces of equipment's reliability values tend to approach ever nearer to zero, but never cross zero. If a piece of equipment is in service for a very long time, and when one is not willing to repair or replace, it will ultimately fail (Goel, 2004).

The difference between reliability, availability, and maintainability is described in Figure 2 below. Reliability data is based on Mean Time to Fail (MTTF) and Mean Time to Repair (MTTR). Maintainability is described Section 1.3.4.

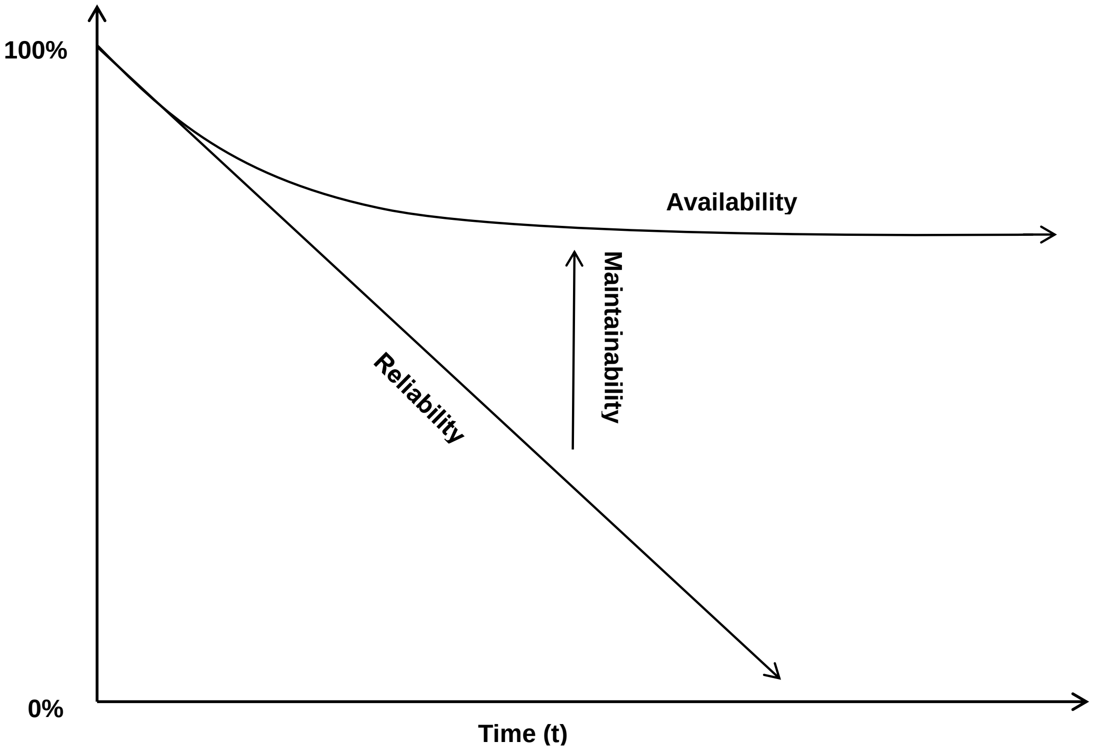


Figure 2: Reliability, Availability and Maintainability

Define:

- R(t) = Reliability;
- A(t) = Availability; and
- M(t) = Maintainability.

Availability is defined as shown in equation (1.1).

$$A(t) = \frac{MTTF}{(MTTF + MTTR)} \qquad (1.1)$$

In principle, availability is reliability plus maintainability as shown in equation (1.2).

$$A(t) = R(t) + M(t) \qquad (1.2)$$

For example, a system has on average 365 days between failures and has corrective maintenance done on it for 21 days. The assumption is made that the system would be repaired to new. As it would be repaired to new the system would fail less in comparison to a system that is repaired to old. When a system is repaired to old it means that the current system is not repaired but only fixed and the availability number would decrease over time if this trend continues (Saraswat & Yadava, 2008). Whereas repaired to new mean that when a system has failed it was replaced with a new system. Hence the system availability is:

$$A(t) = \frac{365}{(365 + 21)}$$

$$A(t) = 94.56\%$$

The following example illustrates that it is imperative to take note of repair times when intending to increase availability albeit it is only a fraction of the overall operational time.

A system functions for 17520 hours and at the end of 17520 hours fail. The repair time is 160 hours. Therefore, the availability of the function is (17520 / 17680), or 99.05%. To increase the availability to 99.50% (which is what management wants) a decision needs to be made on maintainability. This would in essence affect the whole facility. There are two ways to increase availability (Jackson, et al., 2005):

- Option one is to increase the overall run times to 25,000 hours while maintaining the same 160 hour lost time for repairs; and
- Option two is to decrease the time to repair from 160 hours to 90 hours.

The two options mentioned both generate 99.50% availability. One should be very careful in reducing the repair times; the model should reflect what is seen in the facility, in other words, reality.

1.3.3 Production efficiency

If a facility is capable of exceeding market demand by producing more products, this is known as production efficiency. To really understand how production efficiency is measured, it is important to remember that efficiency is often defined as the ability to create or produce something in a manner that results in the least amount of effort for the maximum return. Equation (1.3) defines production efficiency below (Nutaro, et al., 2012).

$$Production\ Efficiency = A(t) \times Fractional\ Capacity \qquad (1.3)$$

“Fractional capacity is defined by the fraction of total production that could be made at any one time (Sutton, 2010).” When a facility operates day and night and is only producing 50% of the desired output as a result of uncontrollable factors such as reduced volume of sales, then the availability is 100%, but its fractional capacity is 50%, so its production efficiency is 50%.

Table 1 shows the example of how production efficiency is calculated. A facility has an agreed volume of 400m³ per hour. Market volume shows the amount of product that could be sold.

The first two hours are easy to understand. The facility is 100% and 80% available of the time and can sell most of what it produces. Thus, if the production yields the full 400m³ per hour the production efficiency is 100%. On hour 3, the availability rises to 100%, so the production efficiency is also 100%. On hour 7, the facility can merely sell 50% of its possible production regardless of the 100% availability. This means its efficiency is 50%. In the last hour, the market volume is 100% and the availability is 0%. Thus, the production efficiency is 0% (Sutton, 2010).

Table 1 shows an example of the production efficiency numbers.

Time (h)	**Market Volume %**	**Availability %**	**Production m³**	**Efficiency %**
1	50%	100%	200	50%
2	50%	80%	160	40%
3	100%	100%	400	100%
4	100%	80%	320	80%
5	100%	100%	400	100%
6	100%	70%	280	70%
7	50%	100%	200	50%
8	100%	100%	400	100%
9	50%	90%	180	45%
10	100%	0%	0	0%
			2540	**64%**

Table 1 Production Efficiency Example

1.3.4 Maintainability

“The maintainability of a failed component or system is the probability that it is returned to its operable condition in a stated period of time under stated conditions and using prescribed procedures and resources. (Ayers, 2012)*”*

“A lot of RAM analyses presume that when a piece of equipment is repaired, it is back to working condition or ‘‘as good as new’’ (Adhikary, et al., 2012).” The fact of the matter is that this theory is seldom true, most equipment is repaired to a state that is anything between new and old. (Mobley, 2014) affirms that “it is in worse condition than when it was brand new, but in better condition than at the time of failure.”

1.3.5 The effect of combining RAM modelling and stochastic simulation on production efficiency

In essence, RAM modelling caters for the availability of a system, sub-system or a piece of equipment and stochastic simulation modelling caters for the amount of volume or throughput produced on any given time. RAM modelling simulates time between failures and time to repair data of equipment to calculate an availability. This beckons the question, what is the influence of RAM modelling and stochastic simulation on production efficiency and how enriching stochastic simulation with RAM modelling will better the bottom line at a company (Jackson, et al., 2005).

Section 1.4 talks about the problem statement.

1.4 Problem statement

Stochastic modelling looks at production efficiency or throughput and reliability modelling looks at understanding the reliability of a piece of equipment or system. RAM modelling addresses the following questions:

- How long is the system or equipment unavailable?
- Why is it unavailable?
- What is the domino effect of this unavailability?
- What is the system availability?
- What is the sub-system availability?

If one knows what the reliability of a certain component or system is, one will also know what effect there will be on throughput for typical production processes. Unfortunately, production at any manufacturing company is not typical. It is highly integrated and includes complexities like feedback loops, use of storage facilities, multiple possible destinations for products, variable rates of operation of different units and impact of bottlenecks.

Many more questions could be answered by combining RAM modelling with stochastic simulation. These answers could add weight to capital expenditure justifications, and contribute to comprehensive evaluations of components and systems.

The main research question is defined in Section 1.5.

1.5 **Main research question**

What is the effect of Reliability, Availability and Maintenance (RAM) modelling and stochastic simulation modelling on production efficiency?

1.5.1 Secondary research questions

- If a component or system has low or high availability, how does this influence the throughput?
- What are the potential critical components and process bottlenecks?
- Which equipment has the highest risk of operational failures?
- What is the production and cost impact of adding or removing equipment?
- What are the “what-if” scenarios and their predictions?
- What are the bad actors or single points of failure?
- What is the impact on system reliability and availability of varying duty cycles, service-life limitations, wear-out items, or environments and conditions?

The hypothesis is in Section 1.6.

1.6 **Hypothesis**

By combing RAM simulation modelling with stochastic simulation techniques one can sustainably improve production volumes to better the bottom line at a manufacturing company.

The method of investigation is explained in Section 1.7.

1.7 **Method of investigation**

1.7.1 Literature review

The current literature available on the effect of RAM modelling and stochastic simulation modelling on production efficiency techniques and all relevant concepts was examined by means of a literature review. All of the sources used were obtained from text books, scientific journals and research documents which are scientifically verifiable.

1.7.2 Case study

A case study will be followed by the literature study where a RAM model will influence a stochastic model as suggested in this study. The methodology used will provide answers posed by the research question.

The design phase of a capital project mainly focused on the engineering and design specifications of the equipment, such as process size, design responsibility and mechanical issues.

Life cycle studies about reliability were seldom done in the past (Adhikary, et al., 2012). Designing for reliability is progressively becoming compulsory and the effects of RAM modelling are critically evaluated in the review sessions by the project management teams.

There are numerous reliability tools and approaches for reliability personnel to use. All approaches have its applications and boundaries. A RAM study is perfect for analysing and illustrating the business benefits and justifications of different scenarios.

“Discrete event simulation, and in this case Arena®, is a tool not traditionally used in continuous environments for design purposes (Kelton, et al., 2015). Arena® is used in a continuous environment during design of modifications to existing facilities and for the identification of infrastructure constraints in blending scenarios. All off the different types of areas the value of Arena® is to vigorously evaluate the changes that is needed in a united environment.

Interactions between facilities can be considered and the influence of integrated operation on planned throughput can be calculated. The impact of failures and scheduled maintenance in the facility modifications can be estimated and any adjustment to infrastructure or facility capacity can be made before money is invested (Meyer, 2004).”

RAM modelling influencing stochastic simulation is currently the status quo of the models executed for capital projects that are currently done by a leading manufacturing company in South Africa.

Points to remember when applying RAM modelling to stochastic simulation models (Jackson, et al., 2005):

- The RAM modeller’s and stochastic simulation modeller’s data needs to be aligned;
- The same time unit measures need to be used in the two models for example; hours, minutes, days etc. Although simulation modelling additionally measures throughput, both models use Mean Time to Fail (MTTF) and Mean Time to Repair (MTTR) data.

Chapter outline described in Section 1.8.

1.8 Chapter outline

Chapter 2 will focus on the research methodology of RAM modelling and stochastic simulation modelling. There will be an in-depth look at what is RAM and stochastic modelling and how is it applied.

Chapter 3 will concentrate on production efficiency and what effect does RAM modelling and stochastic simulation have on production efficiency.

Chapter 4 is a case study that will demonstrate the analysis of RAM and stochastic simulation modelling and how does this calculations impact production efficiency. Sensitivity analysis on reliability data will also be demonstrated.

Chapter 5 will discuss the results and what significant impact RAM modelling and stochastic simulation modelling had on maintenance strategies and how this impacted a manufacturing company.

Chapter 6 is conclusions on the effect of RAM modelling and stochastic simulation modelling on production efficiency.

The conclusion follows in Section 1.9.

1.9 **Conclusion**

RAM modelling calculates the availability of all components in the sub-system. Stochastic simulations have all the sub-systems in its model. Because a stochastic simulation calculates the throughput of the system, RAM modelling and stochastic simulation modelling have the sub-systems in common and that is why the two models overlap with one another (Nutaro, et al., 2012). If one knows what the reliability of a certain component or system is, one will also know what effect there will be on throughput for typical production processes. However, production at a manufacturing company is not typical. It is highly integrated and includes complexities like feedback loops, use of storage facilities, multiple possible destinations for products, variable rates of operation of different units and impact of bottlenecks. By combining stochastic simulation and reliability modelling, the following questions can be answered:

- If a component or system has low or high availability, how does this influence the throughput?
- Which components were the biggest contributors to the downtime experienced?
- Which components were the biggest contributors to the loss of volume throughput experienced?

CHAPTER 2: RELIABILITY, AVAILABILITY AND MAINTENANCE MODELLING

2.1 Introduction

Chapter 2 introduces the research methodology that comprises of literature reviews and an in depth look at what is Reliability, Availability and Maintenance, how is it modelled and how validation is done.

In Section 2.2 an in depth look at quantitative reliability analysis.

2.2 Quantitative Reliability Analysis

“Reliability is the probability that a piece of equipment, product, or service will be successful for a specific amount of time (Calixto, 2016).”

When one needs to explain the reliability of a piece of equipment, product, it is essential to gather historical reliability data, and in this case, failure data. “Consequently, step one in the life cycle analysis is to comprehend how failures happen over time and to explain Mean Time to Fail (MTTF) and Mean Time to Repair (MTTR) to see if equipment is achieving the designed reliability (Wang, 2012).”

Reliability focuses on the ability of a piece of equipment to perform its intended function when one assumes that a piece of equipment is performing its planned function at time equals zero. The definition of reliability can be described as: "*The ability of a piece of equipment to consistently perform its intended or required function or mission, on demand and without degradation or failure. Therefore, the effects of planned maintenance and unplanned maintenance i.e. trips and equipment failures are included* (Adhikary, et al., 2012)."

RAM models to a great extent focuses on the data that will be entered into the model. Reliability data to be entered into the model are MTTF and MTTR. MTTF describes the predicted time between two failures that are recurring and MTTR describes the predicted time to repair a piece of equipment that has failed (Nutaro, et al., 2012).

To manage life cycle analysis about equipment, it is essential to have historical data about all the failure modes that took place. "The failure mode is the manner in which a piece of equipment or product loses part or total capacity to perform its function (Kumar, et al., 2012)." *Numerous companies in the petrochemical industry do not have historical data for the equipment in the facility, and most of the equipment providers have no reliability data for the products they sell. "Thus, the first step in reliability requests is to gather data, but in most circumstances the modeller who needs the data for life cycle analysis is not the same person who repairs or performs maintenance on the equipment and gathers the data. The crux is that there are few companies that have reliability data and a good deal of companies that don't* (Calixto, 2016)."

It must always be in the back of a manager's mind of the importance of gathering reliability data for equipment. "*Furthermore, employees must be proficient in gathering data and making decisions based on dependable data. This is a big challenge for most* *companies, because even when procedures and programs are established, it is necessary to collect, assess, and store failure data in files and reports for future access* (National Research Council, 2012)."

In the case of reliability data, also known as failure and repair data, has not been recorded, such data can originate in numerous bases such as:

- The Offshore Reliability Data (OREDA) handbook (OREDA, 2015);
- Non electronic Parts Reliability Data (Denson, et al., 1995);
- "Availability Analysis Handbook for Coal Gasification and Combustion Turbine based Power Systems (Arnic Research Corporation, 1985)."

Various reliability modellers see past reliability data as an index, which comprises of the following:

- Constant failure rate;
- Reliability;
- Availability;
- MTTF; and
- MTTR.

The Reliability and Maintainability (RM) data for similar equipment may vary considerably in altered sources (Mobley, 2014). "*The reason for this is because the data is dependent on operating situations, the observation size, and period. In this case, period refer to duration. Proper data sources lay the groundwork for the quality of concluding results. Nonetheless, there will always be inequality in the data sets* (Rajpal, et al., 2006)."

The OREDA handbook is the best used data source in the petrochemical industry. It collects data for a large diversity of equipment and systems used in offshore and inland projects. Numerous editions of the OREDA handbook have been issued of which the 6th edition in 2015 is the latest. A computerised database is exclusively available to oil and gas OREDA members (OREDA, 2015).

When RAM analysis takes place, OREDA has the reliability data categorised in failure rate and active repair time. Regarding maintenance data, OREDA caters for both calendar time and operation time. During a RAM analysis, the operational time-dependent data is used. For data that needs to be entered into BlockSim®, the failure rate needs to be converted to MTTF (ReliaSoft Corporation, 2016).

The constant failure rate, which is a function of time, is notably illustrated by the bathtub curve shown in Figure 3:

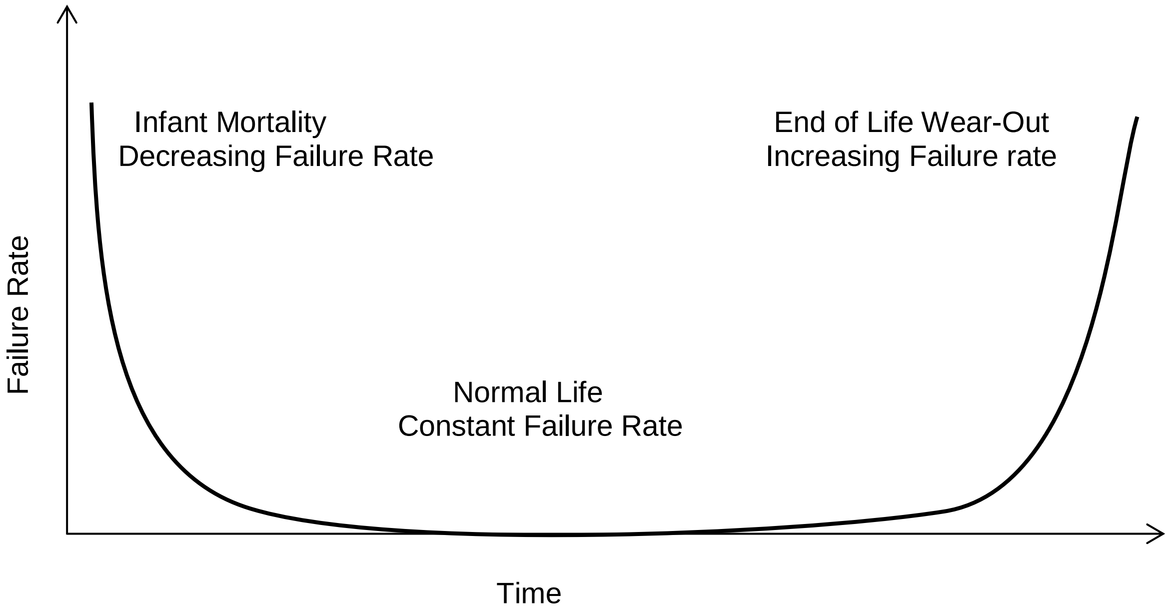


Figure 3: The bathtub curve

When it comes to RAM analysis, it is a widely accepted assumption that the failure rate is constant. This suggests that all ramp up and ramp down failures are ignored. Thus, the constant failure rate implies that the reliability of equipment is measured when it is in a steady state. A life cycle is restricted to the valuable lifetime of the project (Wang, 2012). In saying this, the MTTF is modelled as an exponential distribution in BlockSim® and Arena®.

"*To do a life cycle analysis, the following resulting data, classified by configuration, is required (Calixto, 2016):*

- *Individual or grouped data;*
- *Complete data; and*
- *Interval data."*

A piece of equipment is known as individual data. Grouped historical data comes from multiple pieces of similar equipment. It is very important to evaluate equipment for the life cycle calculation. Past failure data from one piece of equipment need to be tested to see if it is adequate. However, for typical equipment like the one mentioned, there must be a great quantity of data to ensure a reliable life cycle analysis (ReliaSoft Corporation, 2016).

There are many cases lacking sufficient historical data. Such historical data is of utmost importance when viewing a comparable piece of equipment with a similar working function and in workable condition to generate a database. In a working environment it can be a challenge finding similar equipment. In several circumstances maintenance, working, and process situations have an effect on the equipment life cycle. "*When reliability analysis is led in the pre-feasibility stage, similarity is easier to obtain because operational conditions, processes, and maintenance procedures are similar to project requirements* (Calixto, 2016)." However, when one wants to increase the reliability of the life cycle analysis, one should use data that has been historically grouped., In this case it requires considering various equipment that are more or less the same than the equipment in the facility to create Probability Density Functions (PDF) for the equipment evaluated. In addition it is a necessity to validate equipment likenesses, and in projects this is also easier (Goel, 2004).

When historical data is recorded, the data will be known as complete; in this case one needs to establish a time occurrence, preferably in hours. It is very important to know when the operation started as this will be called the beginning of the life cycle of the equipment. The captured maintenance and operational data will assist in validating when the equipment was online (Adhikary, et al., 2012). In some cases where equipment has no failure data, OREDA will be used as a guideline or as input (Calixto, 2016).

Various types of reports might be used upon failure. However, it is easier for all facility personnel, and those working with data, to understand what type of failure occurred, why it occurred, and to assess if the recommendations conducted solved the type of failure, when looking at the defined failure modes. When defining failure modes, all employees should know what type of failure occurred as they are the ones that will capture the failure. Not knowing the type of failure might lead to incorrect capture.

In some cases the equipment used to create PFDs does not fail in the time being observed. “*This is called right censured data and must be included in the analysis for consideration. In the current observed environment, this data is often not taken into account* (Cassady & Kutanoglu, 2005).”

When equipment has failed after the original failure was captured, such information does not get logged. This data is very important, however, and should be included in the model the next time a report is due. It might seem like the equipment had high reliability, but in reality there were unreported failures at the beginning of the equipment life cycle influencing reliability (Jackson, et al., 2005).

Another intervention on historical data configuration is done when there’s no precise data on equipment failure. In such a case one can do research on the same types of equipment, capturing data showing equipment failure in more or less the same circumstances as the equipment in the current operation.

It is challenging when no data is available. In such circumstances a subject matter expert (SME) may be consulted. Such experts have years’ of experience and a wealth of knowledge about the concerned equipment. This information may also be captured in the database.

There are techniques one can use to an advantage to estimate the variable values from the SME opinion (Wang, 2012):

- Aggregated individual method: This method is where SMEs do not meet but make approximations. These approximations are then collected statistically by taking the recognised mean of all the individual approximations.
- Delphi method: In this method, SMEs make their assessments individually and then all the assessments are compiled and showed to the wider group to define.
- Nominal group technique: The nominal group technique is very much the same as the Delphi method, each SME creates an assessment with its own personal

style attached to it. These assessments will be combined in a statistically manner.

- Consensus group method: Individually, each member will contribute to the dialogue and as a group they make a final decision on what the final value will be.
- Bayesian inference methodology: This method is a mathematical approach applied to estimation of data based on knowledge gained from previous experience.

The assumed state “as good as new” suggests that the maintenance events repaired the equipment to an “as good as new” state. When one looks at the assumption “as good as old” it means that a piece of equipment was repaired to a state just before it failed and that the piece of equipment expect to fail much quicker than if it was “as good as new” (Mobley, 2014).

2.2.1 Maintenance strategy based on reliability

Maintenance strategies and philosophies have been a problem since its implementation in industries. No maintenance manager has ever been 100% happy with it. “*Maintenance strategies are important topics, as they take into account the reliability and availability of a repairable system. Good maintenance scheduling of equipment can keep repairable systems’ availability high, circumvent the loss of failure and reduce the waste of cost* (Adhikary, et al., 2012).” The reliability and availability of any system normally deteriorates as system time increases.

It is inevitable that equipment will have to be replaced in the future. But when proper maintenance is done during the equipment's life cycle (Cassady & Kutanoglu, 2005), one is extending the time for it to be replaced. The age-old saying is true when it comes to maintenance of equipment: "Time is money and money is time". "*As was claimed above, according to the time of maintenance, maintenance is usually classified into two major categories, corrective maintenance (CM) and preventive maintenance (PM). CM corresponds to the actions that occur after a piece of equipment fails. PM is also known as facility shut downs or planned maintenance where the system will be out of commission for a certain period of time* (National Research Council, 2012)."

"*The one big advantage of PM is that the system can always be kept in an available condition when needed and the grave damage incurred by the unpredicted fails can be evaded.*

When choosing maintenance strategies the problem is of primary importance in facility management and operation. An effective strategy should aim at guaranteeing the level of performance and availability of the system while consenting for decrease in resource expenditures. (Nutaro, et al., 2012)"

When each aspect of reliability, availability and maintainability is sorted out, and the data updated with all the necessary information, the input to the stochastic simulation can proceed and then the production efficiency can be calculated.

The point is whatever decision made in the RAM environment, big or small, will affect the production efficiency as seen in the case study in Chapter 4. If the RAM model's input changes, the stochastic simulation parameters shift as well and evidently, the production efficiency calculations change too.

Section 2.3 probability density functions is presented.

2.3 **Probability Density Functions (PDF)**

2.3.1 Exponential

The exponential PDF signifies random events over time and best characterises random failures. In Figure 4 the exponential PDF is described as a continuous distribution. Mechanical equipment fail at any stage in its life cycle. Most of all the mechanical equipment will fit this distribution because mechanical equipment fails randomly. If one would know when the equipment was due to fail a normal PDF would fit the failure more accurately (Calixto, 2016). For example, during preventative maintenance strategy or an induced failure, a normal PDF would fit the failure more accurately.

Every time the exponential function is applied to calculate the time to fail, the main assumption is that failures happen randomly over time.

Exponential Distribution

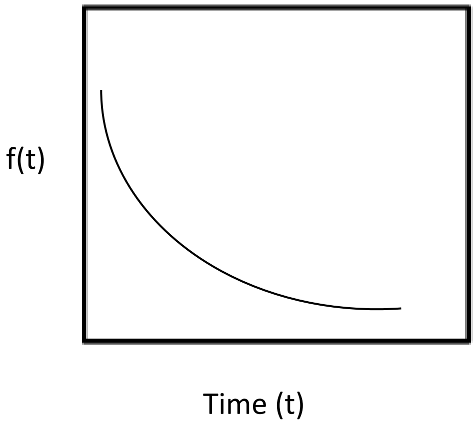


Figure 4: Exponential Distribution

2.3.2 Normal

The normal PDF is a function that is frequently used. It defines the failure that happens and that are under control, which means the failure happens very close to the mean with a standard deviation. Numerous variables from different types of analyses are treated like normal distributions but are not always well represented. When there is a higher standard deviation (in most cases the standard deviation is 10% of the mean) it becomes more difficult to calculate the value. Regarding reliability this is either a sign to repair, or fail (ReliaSoft Corporation, 2016). Figure 5 illustrates a normal distribution PDF.

"Differing from exponential distribution, the normal distribution, also known as a bell curve, has two parameters, namely mean (μ) and standard deviation (σ). These are called position and scale parameters individually. It is essential to notice that whenever σ decreases, the PDF gets pressed toward the mean, which becomes narrower and

taller. In the opposite effect, whenever σ increases, the PDF moves away from the mean, which in essence, it becomes broader and lower (Ayers, 2012).”

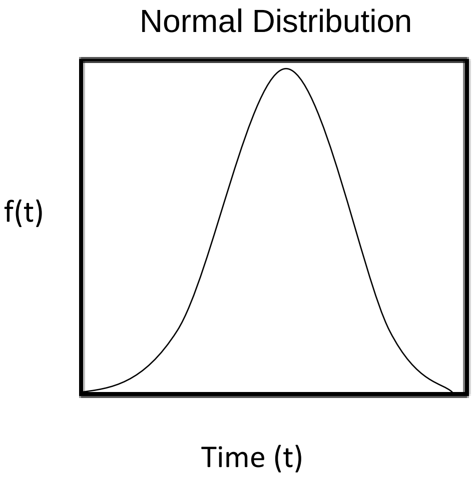


Figure 5: Normal Distribution

2.3.3 Lognormal

When one looks at the lognormal PDF shape, illustrated in Figure 6, it shows that most of the failures happen at the beginning of the life cycle and most often because the installed equipment was incorrect, improperly handled or badly operated. Human error has a great effect on equipment failure happening at the beginning of the life cycle for a piece of equipment (Jackson, et al., 2005)

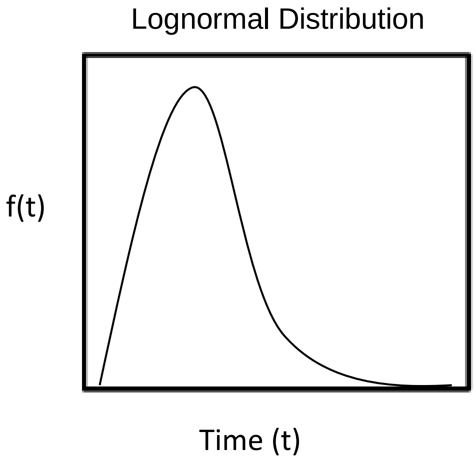


Figure 6: Lognormal Probability Density Function

An Introduction to RAM analysis is defined Section 2.4.

2.4 **Introduction to RAM Analysis**

RAM analysis supports a company to quantitatively define the following (Nutaro, et al., 2012):

- System and subsystem availability and reliability;
- Spare equipment policy impact on system availability;
- Predictive and corrective maintenance policy impact on system and sub system availability;
- Logistic impact on system and sub system availability; and
- Redundancy impact on system and sub system availability.

Implementing RAM analysis makes it reasonably possible to discover the system availability, reliability, and maintainability of equipment quantitatively and which critical sub-systems and equipment has the biggest impact on facility performance. “RAM analysis can be done for one piece of equipment or with numerous pieces of equipment for a multifarious system with several pieces of equipment. When a system is not achieving the desired availability goal, the equipment responsible for most of the downtime will be identified and upgraded approvals can be tested by the simulation model to predict system and sub system availability. (Calixto, 2016)”

Defining the scope of work is elaborated in Section 2.5.

2.5 **Defining the scope of work**

The scope of work (SOW) is very important and the first step of the RAM analysis process. The SOW is defined based on the objective, time constraints, and customer requests (Adhikary, et al., 2012). One needs to ensure not to underestimate the effect of bad performance. Often significant system weaknesses aren’t analysed sufficiently or the emphasis of the analysis fluctuate and such weaknesses are not taken into account in the RAM analysis. If that happens, more time must be allowed than what was originally captured in the SOW to include such weaknesses in the RAM analysis. Thus, more time will be needed to complete the project (Goel, 2004).

Section 2.6 is an in depth look at analysing reliability data.

2.6 **Analysing reliability data**

"*Looking to safeguard the correct depiction of data, maintenance activities, and facility, process, and reliability professionals with knowledge of these types of systems are created in this stage of the RAM modelling process and a quantitative analysis of the life cycle of the equipment is performed* (Kumar, et al., 2012)."

"A downtime equipment criticality analysis of the causes of system unavailability is also performed. All equipment failure modes are being standardised. (Ayers, 2012)" It is important when writing reports that all equipment in a specific system are well defined to avoid confusion caused by the fact that more than one "piece of equipment will have the same failure and repair data (Jackson, et al., 2005)."

"If historical failure data is available, the equipment's reliability data is treated statistically to describe the PDF that is the best fit for the data (ReliaSoft Corporation, 2016)." When no data is available, one needs to define the triangular function that best represents the different failure modes. This could be seen as highly optimistic and most probable failure times depending on each reliability time. This approach will work more effectively when it is applied to the repair time PDFs. Most of the repair times on reports also include logistic time as delayed time to deliver a component or equipment when a spare part was unavailable. Many of the facility personnel and SMEs have their doubts about the repair time, and to distinguish what is being considered as maintenance activity it is good practice to describe what will be done when maintenance is being carried out.

Reliability data analysis is very important to RAM analysis results, and proper time management is needed to guarantee RAM analysis quality (National Research

Council, 2012). Failure and repair time data analysis is time consuming, there is often not enough time allocated and operations researchers' move on to the modelling and simulation stage the in RAM analysis.

Modelling and simulation is defined in Section 2.7.

2.7 **Modelling and simulation**

To describe system and sub system availability, equipment PDF parameters need to be defined as input into a system, "*a Reliability Block Flow Diagram (RBD) must first be defined and then simulated. To describe a system RBD it is necessary to demarcate the system's limits prior to execution of the analysis*. (Sutton, 2010)" Most of the time an evaluation of sub-systems, equipment, and components are available. Failures of these sub-systems, equipment, and components effect production loss. When one creates a RBD it is important to define a logic effect for any equipment in the system. Thus, the modeller will need to know if the failure of certain equipment means it is switching the system on or not (Wang, 2012).

"*If a piece of equipment fails and causes system downtime, a system like that is modelled in series. Though, if two or more pieces of equipment fail and doesn't switch off the system that type of equipment is modelled in a parallel block, and the whole parallel block is in series with the other blocks.*

Thus, it is necessary to set up model equipment using block diagram procedures and be familiar with the mass balance details influencing losses in productivity (ReliaSoft Corporation, 2016)."

“To get the availability results after modelling the system in a RBD format it is important to use a recognised approach for example Monte Carlo simulation (Hojjati & Noudehi, 2015).” When simulating a whole system, each block that representing one specific piece of equipment will have its own reliability data.

“*Thus, Monte Carlo simulation will continue with failures over simulation time for all block PDFs which consists of reliability data. While doing this, if a block fails and it is in series in the RBD, the unavailability will be counted in the system for failure and repair duration over simulation time. Simulation time hinge on how long the system functions based on time recognised* (Calixto, 2016).”

2.7.1 Monte Carlo Simulation

“*The basis of a Monte Carlo simulation is the generation of random numbers. A random number generator is a computational algorithm that generates repeated random numbers* (Ritter, 2013).”

Monte Carlo simulation calculates the mean of the output distribution by calculating all of the random generated numbers and dividing it by the number of samples.

“The Monte Carlo simulation technique simulates the available uncertainty in the modelling output. This uncertainty is triggered by changing the input variables coming into existence because of different factors; in this case it is the failures and the repair times. When repeating simulation cycles with a large number of times, the results are closer to reality (Hojjati & Noudehi, 2015). “

2.7.2 Reliability Block Flow Diagram

The RBD configuration consists of series configurations and parallel configurations or a combination of both. Figure 7 consists of a series configuration (ReliaSoft Corporation, 2016).

Figure 7: Series configuration

When RBD blocks are in series, it means that anyone of A or B can switch of the system.

In equation 1.4 the reliability of the system will look as follows:

$$R_S = R_A R_B \qquad (1.4)$$

Figure 7 illustrates that if equipment A or B would fail that A and B would be offline.

Figure 8 illustrates a parallel configuration.

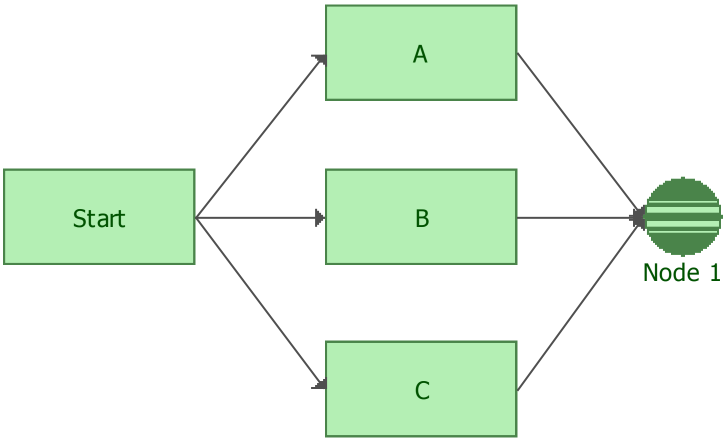


Figure 8: Parallel configuration

Equation 1.5 describes the parallel system of equipment

$$R_S = [R_{\frac{1}{3}} (1 - ((1 - R_A)(1 - R_B)(1 - R_C)))] \qquad (1.5))$$

Figure 8 shows a parallel configuration with a logistic node. Such a logic configuration is characterised by the logic node (k/n = 1/3), meaning that the system needs only 1 out of the 3 to function properly for the system to be available. In principle, if equipment A and B would fail, the system would still be available with equipment C is still functional.

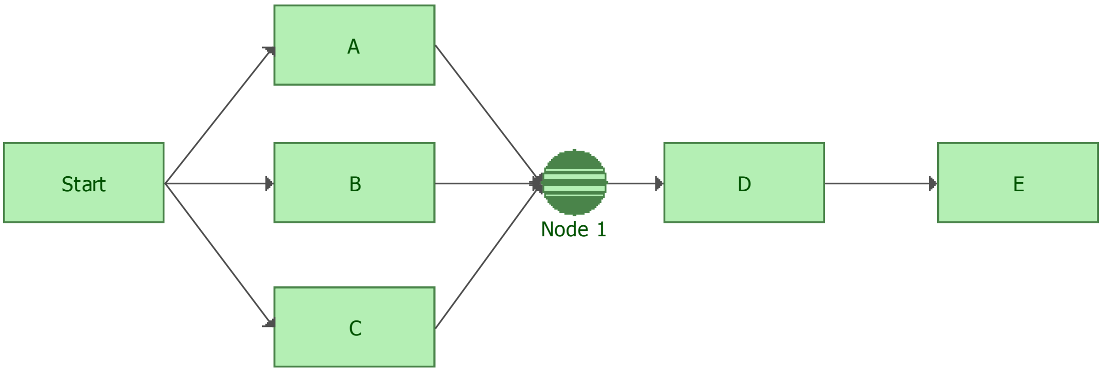


Figure 9: Combination of series and parallel configurations

Equation 1.6 describes the combination of series and parallel.

$$R_S = [R_{\frac{1}{3}} (1 - ((1 - R_A)(1 - R_B)(1 - R_C)))] \, R_D R_E \qquad (1.6)$$

Figure 9 shows a combination of series and parallel configurations. If either equipment D or E would fail, one would have total system failure. If the logic node is (k/n = 1/3) or 1 out of 3, A, B and C would need to fail for a total system failure.

Sensitivity analysis will be presented in Section 2.8.

2.8 Sensitivity analysis

One of the foremost objectives of RAM analysis is to calculate overall availability for the system and identify the equipment that is responsible for the system unavailability (Goel, 2004).

Enhancement opportunities that can be applied are:

- Defining the policy around spare parts;
- Maintenance policies;
- The number of redundancies; and
- Reducing the amount of equipment in systems.

To test system configuration, RAM analysis is also a good opportunity as it is probable to use numerous assumptions in the RBD and simulate to discover the impact it has on the overall availability (Calixto, 2016).

Model validation and prediction to follow Section 2.9.

2.9 **Model validation and prediction**

A quantitative viewpoint states that validation is the process of measuring if the quantity of interest (QOI) for an existing system is within an approximated endurance, this is based on the planned use of the model prediction. However, most of the time prediction occasionally refers to circumstances where no data is available, in this case, reference is made to the output of the model (National Research Council, 2012).

"*Validation can be accomplished by directly comparing model outputs to facility output for the QOI and computing a confidence interval for the difference, or carrying out a hypothesis test of whether or not the difference is greater than the tolerance* (National Acadamy of Sciences, 2010)." In further settings, a more complicated statistical modelling formulation requires a combined simulation output with different kinds of physical observations, as well as SMEs to create a prediction with add-on prediction uncertainty, which can formerly be used for the assessment (Wang, 2012).

Evaluating prediction uncertainty is vital for both validation and prediction of non-measured QOIs. This doubt characteristically originates from several sources, comprising the following:

- Absence of knowledge about input in the model;
- The difference between model and reality;
- Limited evaluations; and
- Programming mistakes.

"*In typical cases, the verification effort can successfully eradicate the uncertainty due to solution and coding errors, with only the first three sources of uncertainty remaining. Similarly, when the simulation model runs quick, one can evaluate the model at any required input setting, rejecting the need to evaluate what the model would have produced at an untested input setting*. (Ritter, 2013)"

The validation and prediction protocol during a basic process includes (Wang, 2012):

- Recognising major vagueness;
- Identifying observations;
- Tests;
- Evaluating prediction uncertainty;
- Evaluating the quality of the prediction;
- Providing evidence on how enhance an valuation; and
- Interactive sessions.

"*Identifying and indicating uncertainties generally involves a sensitivity analysis to determine which inputs of the model affect key model outputs. When the uncertainties are identified, one must determine how best to represent these important contributors to uncertainty* (Calixto, 2016)."

"*The available physical observations are fundamental to any validation assessment. In some cases such data is observational, provided by nature e.g., atmospheric measurements and supernova lights. In other cases, data come from a carefully planned hierarchy of controlled experiments. In adding to physical observations, data may come from the literature or SME's integrating historical data or known physical behaviour* (Wang, 2012)."

Estimating prediction uncertainty requires the combination of calculated models, physical observations, and other information sources. How this estimation is supported can range from very straight forward, as in the weather forecasting to quite complicated systems. In these examples, some physical observations are used to refine or constrain uncertainties that contribute to prediction uncertainty.

"For any prediction, evaluating the quality or reliability of the prediction is vital. The concept of prediction reliability is more qualitative more than anything else. Prediction reliability includes (Adhikary, et al., 2012):

- *Verifying the assumptions or operating rules on which an estimate is based;*
- *Examining the available of physical measurements;*
- *The features of the computational model; and*
- *Applying a skilled verdict."*

"*In different validation applications, opportunities exist to do extra experiments to expand the prediction uncertainty and the reliability of the prediction. Estimating how different forms of extra information will improve predictions or the validation* *assessment is an important component of the validation effort. This can help with decisions about where to invest resources, how long one should do corrective maintenance and how much spare equipment one should keep in order to maximise the reduction of uncertainty and an increase in reliability* (Cassady & Kutanoglu, 2005)."

Communicating the results of the prediction analysis is done using both quantitative and qualitative aspects. "*While the communication component is not essentially calculated, effective communication may depend on mathematical characteristics of the assessment.*

The numerous tasks stated in the previous paragraphs give a comprehensive outline of validation and prediction. Precisely how these tasks are supported depends on the features of the specific application. The list below covers a multiple considerations that will have an effect on the methods and approaches for carrying out validation and prediction (National Research Council, 2012):

- *The total amount of relevant physical observations for the assessment;*
- *The correctness and uncertainty escorting the physical observations;*
- *The difficulty of the physical system being modelled;*
- *The computing infrastructure and run time demands of the model;*
- *The correctness of the computational model's solution comparative to that of the numerical error;*
- *The correctness of the computational model's solution relative to that of the true model discrepancy;*

- *The presence of model parameters that need calibration using the available physical observations, and*
- *The availability of alternative computational models to assess the impact of different modelling techniques*."

Results and recommendations defined in Section 2.10.

2.10 **Results and recommendations**

RAM analysis results and recommendations is very useful tool to help with decision support. "*It must be assessed and reinforced by management to achieve objectives to maintain or improve the current system availability. When comparing it to different tools, RAM analysis is very complex system, and lot of people because of the complex mathematics and software knowledge requirements, struggle with it. It is good practice to create a document that it is called the RAM project document that includes the objectives, diagrams, results and recommendations. If more information is required about specific points, they can go through the report* (National Research Council, 2012)."

CHAPTER 3: PRODUCTION EFFICIENCY

3.1 Introduction

“*Production efficiency is the actual production divided by the maximum potential production or market volume that could be achieved if the unit were to operate without failure throughout its operating life. Production efficiency fully accounts for periods of degraded operation resulting from equipment failures, planned and unplanned outages* (Calixto, 2016).”

In this chapter the author will describe production efficiency with stochastic simulation modelling without RAM modelling and production efficiency with stochastic simulation modelling with RAM modelling with examples.

In Section 3.2 production efficiency with only stochastic simulation modelling is explained.

3.2 **Production Efficiency with only Stochastic Simulation modelling**

Production Efficiency is determined with a high-level stochastic simulation model and used to predict and analyse the throughput estimate for the facility design. Arena® is the preferred software for calculating production efficiency.

Arena® is a discrete event simulation modelling tool used to predict the system wide impact of operating rules and alternatives including reduced capacity during failures or phased shutdown, ramp-up as well as impact of buffers. A model needs to run in hourly intervals with a simulation length of x years and for numerous repetitions.

This simulation model uses a single overall failure rate, MTTF and MTTR, for a unit or subsystem. Depending on the failure, the distribution for MTTF could be a normal distribution, for planned maintenance, or exponential distribution if one doesn't know when the failure transpires. When it comes to MTTR, it is usually a triangular or normal distribution to include variability (Meyer, 2004). An example of how a typical model would look with failure rates included is depicted in Figure 10. A, B, C, D, and E represents units of a system which are in series, meaning that if either one of the units fail, it will bring down the system.

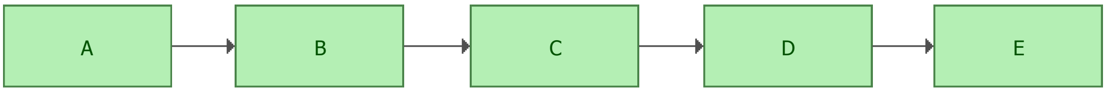


Figure 10: Stochastic simulation modelling configuration

The data that will be entered into the model is as follows in Table 2:

	MTTF (hours)		MTTR (hours)		
Unit	**Distribution**	**Mean**	**Distribution**	**Mean**	**Standard Deviation**
A	Exponential	8760	Normal	22	2.2
B	Exponential	2190	Normal	42	4.2
C	Exponential	6570	Normal	25	2.5
D	Exponential	4380	Normal	30	3
E	Exponential	8760	Normal	21	2.1

Table 2 Reliability data for stochastic simulation model

The Production Efficiency model considers the following assumptions:

- Reduced rates as a result of failures;
- Ramp-up time after a shutdown or breakdown;
- Planned shutdown sequencing;
- Impacts of tanks; and
- Operating rules (alternative flow during failures):
    - If a unit is shut down, can feed be rerouted to an alternate destination?
    - What backup volume is available for downstream facilities?
    - Are there recycle options to keep the unit hot?
    - What shuts down first and under what conditions?

When the model simulates for 70080 hours or 8 years and 200 repetitions, the production efficiency answer will be 96.61%.

When looked at the model results it will show that Unit B is responsible for most of the downtime as shown in Table 3.

Unit	% Downtime
A	10.50%
B	42.81%
C	14.40%
D	21.65%
E	10.64%

Table 3 Downtime Index for stochastic simulation

Stochastic simulation shows what the integrated effect storage, ramp-up, ramp-down and shut downs have on the system (Meyer, 2004). It also shows which unit was responsible for most of the downtime and in this case it was unit B with 42.81%. What the model doesn’t show is what equipment was responsible for the 42.81% downtime and if one would fix that equipment, does the production efficiency increase? In principle it means, one increases the MTTF and decreases the MTTR; the availability improves and the production efficiency increases as well.

Production efficiency with stochastic simulation modelling and RAM modelling described in Section 3.3.

3.3 Production Efficiency with Stochastic Simulation and RAM simulation

Trying to prove that when the whole system is modelled with all of its equipment included, future practises will not make decisions without it. Taking the same example as in Section 3.2, but showing the equipment in Unit B, to prove it is worthwhile to add equipment to their current model to see the full picture. The availability of Unit B will stay the same as it will now have the equipment in it responsible for the availability it currently has as shown in Figure 12. Unit B is made red for illustration purpose so that one will see that Unit B doesn't have an overall distribution as in Section 3.2. The equipment was modelled in BlockSim® software. The equipment configuration for Unit B is depicted in red below in Figure 11. It is now possible to see what equipment is responsible for the 42.81% downtime.

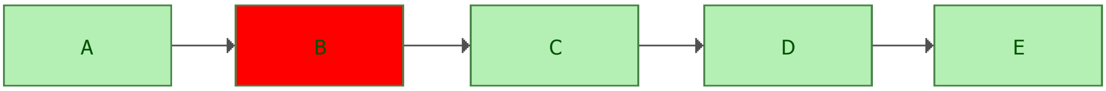


Figure 11: Stochastic Simulation modelling with RAM configuration

Equation 1.7 shows the system configuration for Figure 11.

$$A_S = A_A A_B A_C A_D A_E \qquad (1.7)$$

The Figure 12 below shows how a series configuration looks like in Unit B.

Figure 12: Unit B - RAM model configuration with equipment

Equation 1.8 depicts the sub system availability of Unit B

$$A_B = A_1 A_2 A_3 \qquad (1.8)$$

The reliability data for the equipment mentioned is in Table 4 below.

	MTTF (hours)		MTTR (hours)		
Equipment	**Distribution**	**Mean**	**Distribution**	**Mean**	**Standard Deviation**
1	Exponential	2500	Normal	42	4.2
2	Exponential	8760	Normal	20	2
3	Exponential	35040	Normal	10	1

Table 4 Reliability data for RAM model

When the overall model has been re-run, the overall answer differs slightly from the original. This is because there is more equipment in the model. The model reflects the whole system with all the pieces of equipment that is configured correctly. Standard deviation is 10% of the mean. The overall answer now with all the changes made is 96.12%. It is a 0.5% difference from the original without RAM modelling. A production facility that produces large quantities of volume and makes a mistake of 0.5% has a massive impact on revenue. If a facility produces 100 000 barrels a day, 0.5% is 500 barrels per day. Multiply that with 30 days and it adds up to 15000 barrels. If one would multiply that with the current dollar price, the sum equals to 210 000 South African Rand. Now the 0.5% impact is not so small anymore.

In the answers calculated on the next page, equipment 1 is 73.39% responsible for the 3.88% overall downtime of the system as seen in Table 5.

Equipment	% Downtime
3	5.32%
2	21.29%
1	73.39%

Table 5 Downtime Index for RAM model with stochastic simulation model

If equipment 1 is repaired to new and reliability figures are again that of world practises, the production efficiency should increase. The opportunities are endless. The moment when the whole system is modelled with all of its equipment, one has a proper model that could be used for future practises. One would see the impact on the whole system when:

- Equipment is added;
- Equipment is removed for an extended period;
- Storage is improved or reduced;
- Volumes are reduced; and
- What effect facility maintenance would have on the total system?

The only disadvantage of adding RAM to the overall system is that it is time consuming. Stochastic simulation modelling on its own doesn’t have RAM included in its calculation. For each unit there will be a certain amount of failures generated by the model. RAM modelling will say that each failure happened at x hours and got repaired in y hours in the overall simulation. These are the typical answers that RAM modelling produces and that will feed into the stochastic model to improve production efficiency.

But, comparing the pros versus the cons when building a model, the impact of RAM on the system is undeniably huge and no facility should go without it.

CHAPTER 4: CASE STUDY

4.1 Introduction

The aim of this chapter is to demonstrate that the purpose of the RAM and stochastic simulation models are to calculate the production efficiency for the facility design by:

- Defining the overall facility availability using reliability models;
- Defining the overall production efficiency using stochastic modelling;
- Identifying the critical equipment and systems that contribute to lost production;
- Defining the frequency and duration of outages with subsequent rate reduction;
- Identifying the critical units and tanks contributing to downtime and reduced rates.

Production efficiency is determined with a high-level stochastic simulation model and used to predict and analyse the throughput for the facility design. Throughput impacts due to ramp-up time after shutdowns or failures, planned shutdown sequencing, tank sizing and operating rules (alternative flow options during failures) are considered.

Section 4.2 has the facility layout explained.

4.2 Facility layout

Figure 13 below depicts the layout of Unit A. For the case study the focus will only be on Unit A. The facility starts off with mechanical and electrical heat exchangers and both of them are redundant, one active and one on standby. This is then connected to a 2×50% pump configuration. From the pump system, feed lines connect to a 2×50% filter unit configuration. The filter unit drains directly into a tank which will then feed the final product to three trucks.

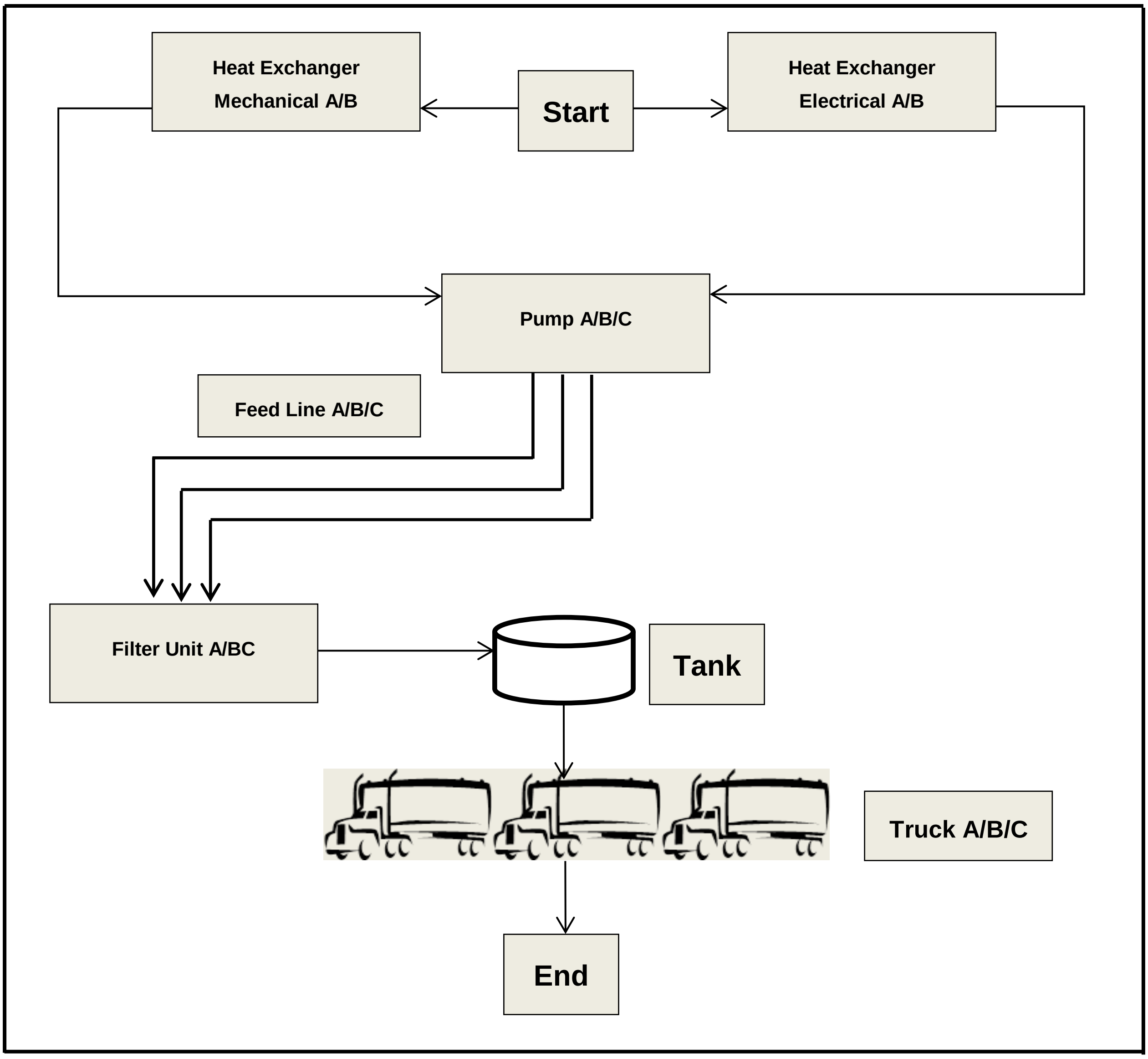


Figure 13 Unit A layout

RAM simulation is described in Section 4.3.

4.3 RAM simulation modelling

RAM models are used to define an availability value. This technique identifies the critical equipment or systems that contribute to lost production and define the frequency and duration of outages. The RBD diagram with parallel and series equipment configurations isn't the same as the Process Flow Diagram (PFD) provided by the facility. No volumetric result is included as part of the RAM study.

The model runs in hourly intervals with a simulation length of 35040 hours or 4 years and for 5000 repetitions.

RAM modelling is simulation based modelling used to predict and analyse the life cycle of equipment systems in terms of reliability, availability and maintainability.

RAM modelling takes the following into account:

- The proportion of time a system is in a functioning condition and able to operate;
- Ability of equipment, machine, or systems to consistently perform its intended or required function or mission;
- Includes unplanned failures (i.e. trips and equipment failures); and
- Assumes repair to new.

Initial start-up period of the facility and ramp-up and ramp-down times are excluded from this calculation. Ramp-up and ramp-down are covered in process efficiency calculations. The RBD of the proposed facility is in the Figure below.

4.3.1 Reliability Block Flow Diagram of Facility

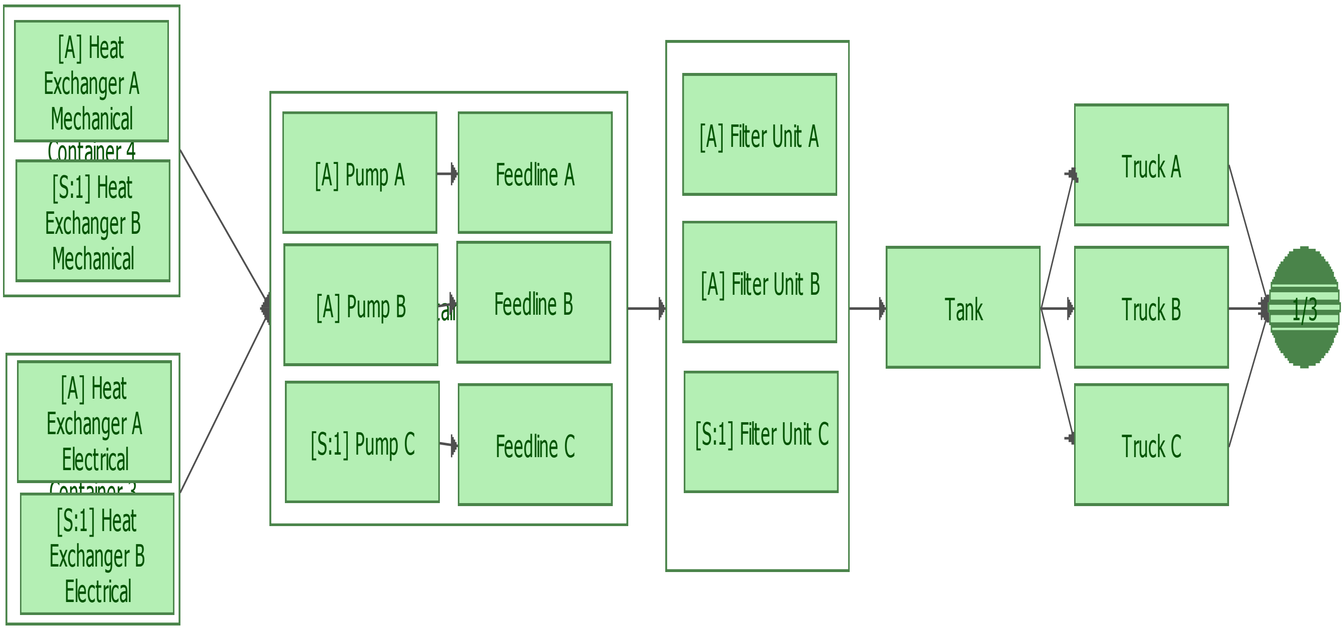


Figure 14 Reliability block flow of facility

Figure 14 illustrates the RBD of the facility. The RBD consists of a complex configuration of series and parallel connections as described in 4.3.

4.3.2 Equipment data

Table 6 contains all the reliability data for Unit A.

	MTBF			MTTR		
Equipment	Distribution	Mean (hours)	Years	Distribution	Mean (hours)	Std dev
Feedline A	EXP	1752	0.20	NOR	24	2.4
Feedline B	EXP	1752	0.20	NOR	24	2.4
Feedline C	EXP	1752	0.20	NOR	24	2.4
Filter Unit A	EXP	25.76	0.00	NOR	3.24	0.0967
Filter Unit B	EXP	25.76	0.00	NOR	3.24	0.0967
Filter Unit C	EXP	25.76	0.00	NOR	3.24	0.0967
Heat Exchanger A Electrical	EXP	100000	11.42	NOR	56	5.6
Heat Exchanger A Mechanical	EXP	100000	11.42	NOR	56	5.6
Heat Exchanger B Electrical	EXP	100000	11.42	NOR	56	5.6
Heat Exchanger B Mechanical	EXP	100000	11.42	NOR	56	5.6
Pump A	EXP	8760	1.00	NOR	76	7.6
Pump B	EXP	8760	1.00	NOR	76	7.6
Pump C	EXP	8760	1.00	NOR	76	7.6
Tank	EXP	70080	8.00	NOR	48	4.8
Truck A	EXP	2555	0.29	NOR	72	7.2
Truck B	EXP	2555	0.29	NOR	72	7.2
Truck C	EXP	2555	0.29	NOR	72	7.2

Table 6 Unit A equipment reliability data

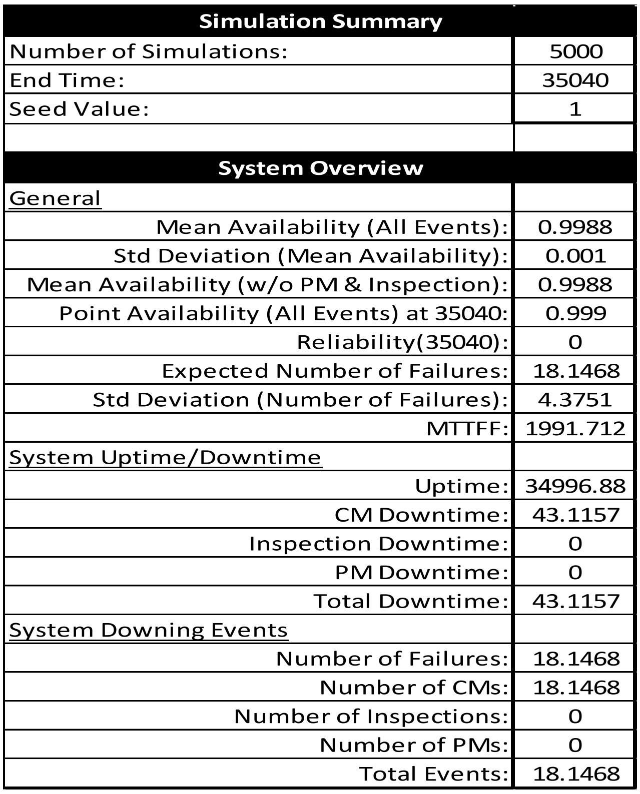
This methodology makes a constant failure rate assumption. This means that the failure rate is independent of age while functioning. An exponential (EXP) distribution is used for MTTF, as one does not know when a failure occurs. A normal (NOR) distribution is used as one has data to verify repair time and know how long it takes to repair equipment.

A mean time to failure (MTTF) and mean time to repair (MTTR) is calculated for each identified failure type. Equipment may have multiple failure types. An assumption has been taken of a standard deviation of 10% from the mean on Normal PDF for MTTR.

Results from the RAM model in Section 4.4 presented.

4.4 **Results from the RAM model**

The RAM model simulation summary is in Table 7 below and an output from BlockSim® software:

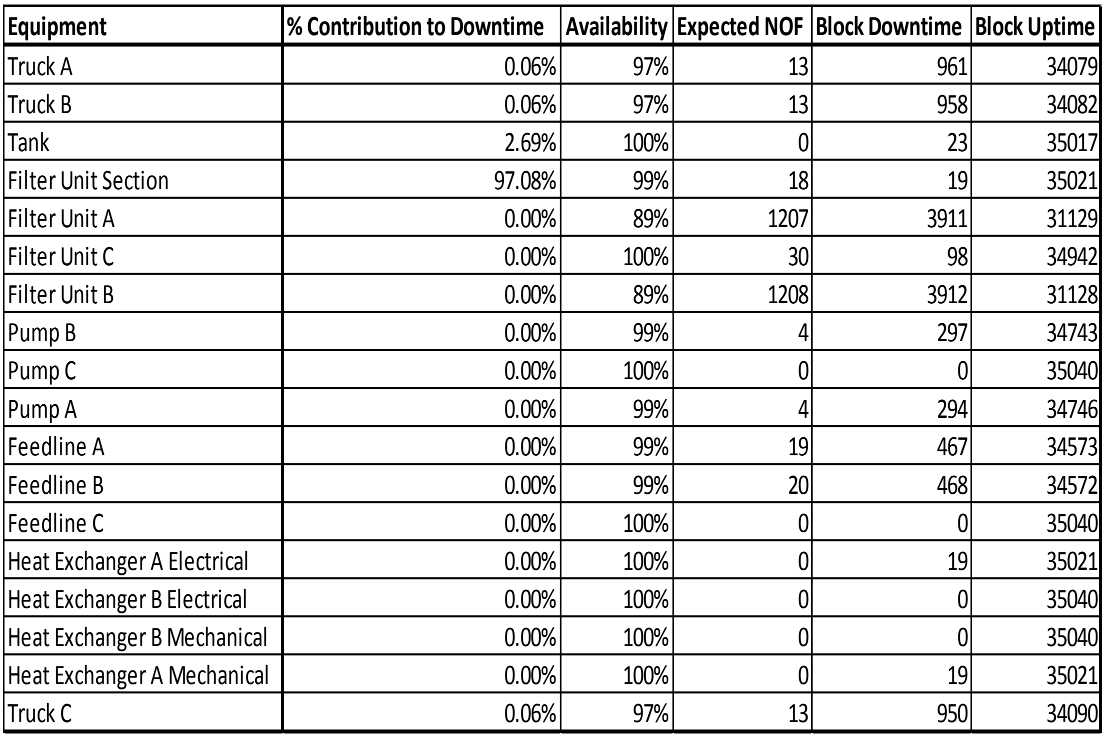


Simulation Summary	
Number of Simulations:	5000
End Time:	35040
Seed Value:	1
System Overview	
General	
Mean Availability (All Events):	0.9988
Std Deviation (Mean Availability):	0.001
Mean Availability (w/o PM & Inspection):	0.9988
Point Availability (All Events) at 35040:	0.999
Reliability(35040):	0
Expected Number of Failures:	18.1468
Std Deviation (Number of Failures):	4.3751
MTTFF:	1991.712
System Uptime/Downtime	
Uptime:	34996.88
CM Downtime:	43.1157
Inspection Downtime:	0
PM Downtime:	0
Total Downtime:	43.1157
System Downing Events	
Number of Failures:	18.1468
Number of CMs:	18.1468
Number of Inspections:	0
Number of PMs:	0
Total Events:	18.1468

Table 7 Simulation summary of RAM model

Overall availability calculates to a percentage of 99.88%. Table 7 shows the biggest contributors as to why the overall facility has an unavailability of 0.12% over a 4-year period. The reliability is 0 at 35040 hours because the system was down at that time and point availability is 99.90% at that specific event in time. Corrective maintenance (CM) is the function if equipment fails, it gets logged and then repaired as quickly as possible. Preventative maintenance (PM) happens once a year or as planned by management. A whole section of the facility will be switch off and all equipment will then be replaced, not because the equipment has failed but to make sure the equipment is in good working order and the probability that it would fail becomes increasingly less. The effect of PM will be shown in the stochastic simulation model to see the impact on volume.

Table 8 is the output file generated from the model. The calculation of the "% Contribution to Downtime" in Table 8 works as follows: Each piece of equipment contributes to the total unavailability of 0.12% and in this case, the Filter Unit Section contributes 97.08% of 0.12% unavailability.



Equipment	% Contribution to Downtime	Availability	Expected NOF	Block Downtime	Block Uptime
Truck A	0.06%	97%	13	961	34079
Truck B	0.06%	97%	13	958	34082
Tank	2.69%	100%	0	23	35017
Filter Unit Section	97.08%	99%	18	19	35021
Filter Unit A	0.00%	89%	1207	3911	31129
Filter Unit C	0.00%	100%	30	98	34942
Filter Unit B	0.00%	89%	1208	3912	31128
Pump B	0.00%	99%	4	297	34743
Pump C	0.00%	100%	0	0	35040
Pump A	0.00%	99%	4	294	34746
Feedline A	0.00%	99%	19	467	34573
Feedline B	0.00%	99%	20	468	34572
Feedline C	0.00%	100%	0	0	35040
Heat Exchanger A Electrical	0.00%	100%	0	19	35021
Heat Exchanger B Electrical	0.00%	100%	0	0	35040
Heat Exchanger B Mechanical	0.00%	100%	0	0	35040
Heat Exchanger A Mechanical	0.00%	100%	0	19	35021
Truck C	0.06%	97%	13	950	34090

Table 8 Biggest Contributors to Downtime in the Unit A facility.

The Filter Unit Section contributes 97.08% to the unavailability. In essence, the filter unit section with its three filters is responsible for the 97.08% of the unplanned maintenance in the proposed facility.

Section 4.5 is describing validation between reality and simulation.

4.5 Validation between reality and simulation

Figure 15 depicts the validation between reality and simulation.

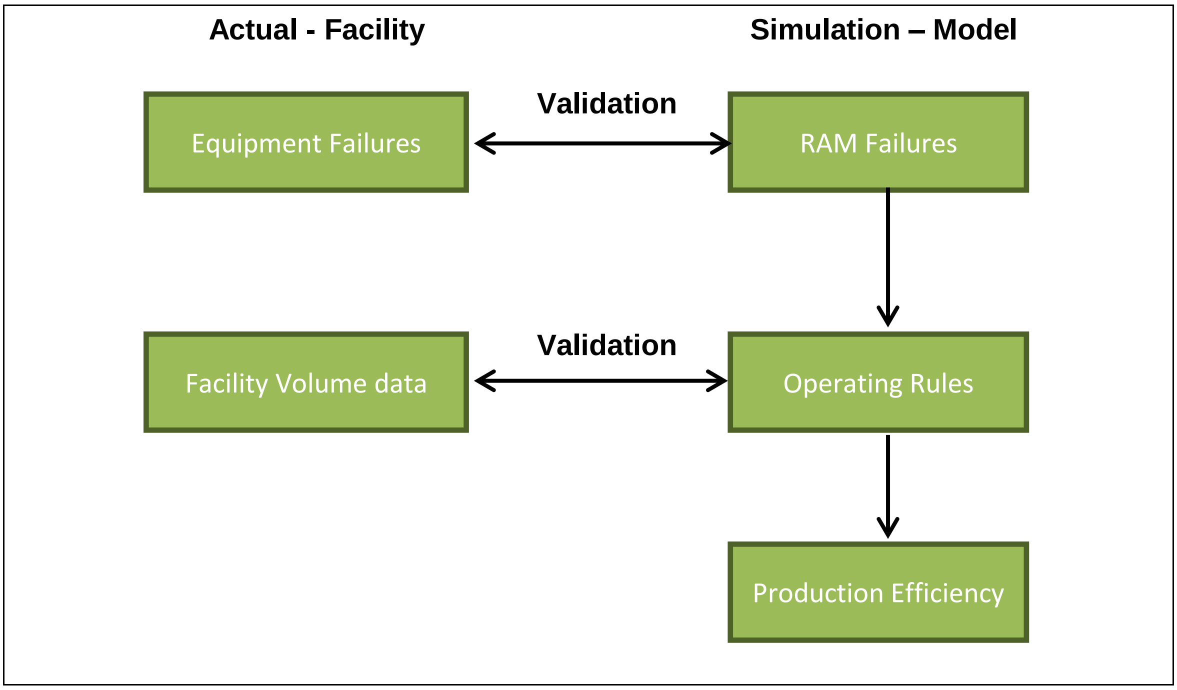


Figure 15 Validation between simulation and actual

The maintenance and reliability department is responsible for storing files containing historical equipment failure data. Equipment failure data is prepared by the RAM modeller and entered into the RAM simulation model. When data is not available from the facility OREDA is used as input.

In Section 4.4 a simulation summary is given of an output file generated by the software. The expected failure number (FN) should coincide with the data received from the facility. A process flow diagram is given to the RAM modeller and the facility is developed accordingly to the equipment that switches the facility on or off.

The file generated by the facility and generated by the RAM modeller looks as follow in Table 9:

	Total Failures
Facility data - Actual	43
Simulation output - FN	43.11

Table 9 Equipment failure validation file

It is clear that the output file generated by the facility and the expected FN are the same. Validation between facility and simulation data is crucial. For the number to be exact or statistically correct the configuration in the RAM needs to be correct as well. Once validated, the RAM results are used as input into the stochastic simulation model.

Facility volume data, also known as mass balance data, is used as input into the stochastic simulation model. Mass balance is based on the principle of volume in equals volume out irrespective of quantity produced.

Validation includes the comparison of actual results and simulation results. All operating rules used in the stochastic model, including the operating philosophies, need to be validated. Within the manufacturing environment, the stochastic model is deemed valid if the deviation between actual data and simulation results are within a

5% range. Exceptions do occur in cases where actual data is not available or the deviations can be explained e.g. change of philosophies or demand during the year.

Sensitivity analysis on MTTF reliability data is detailed in Section 4.6.

4.6 Sensitivity Analysis on MTTF Reliability data

When one wants to implement MTTF it has to go through rigorous simulation testing. First, one needs to test the MTTF with different RBD configurations to get the desired results. There are three RBDs that will be used three times each with different MTTFs. Equipment in the model will be noted as follow:

R_S = Reliability of the system;

R_{eq1} = Equipment 1;

R_{eq2} = Equipment 2;

R_{eq3} = Equipment 3; and

R_{eq4} = Equipment 4.

The three RBD configurations Figure16, Figure 17 and Figure 18 are:

1. All four pieces of equipment are in series.

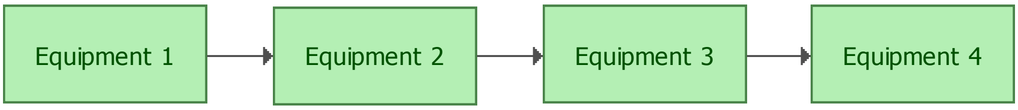


Figure 16 Series configuration

The equation for the above configuration looks as follow:

$$R_S = R_{eq1}\, R_{eq\,2} R_{eq3} R_{eq4} \qquad (1.9)$$

2. Half of the equipment is in parallel and the other half in series.

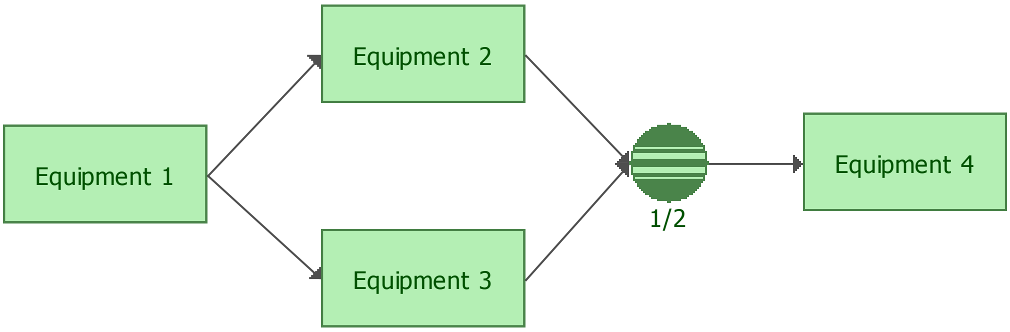


Figure 17 Half parallel and half series configuration

Equation 1.10 depicts Figure 17:

$$R_S = [R_{\frac{1}{2}}\, (1 - \left((1 - R_{eq2})(1 - R_{eq3}) \right))]\, R_{eq1} R_{eq4} \qquad (1.10)$$

$R_{1/2}$ depicts the 1 out of 2 node in the configuration.

3. Three pieces of equipment in parallel and one in series.

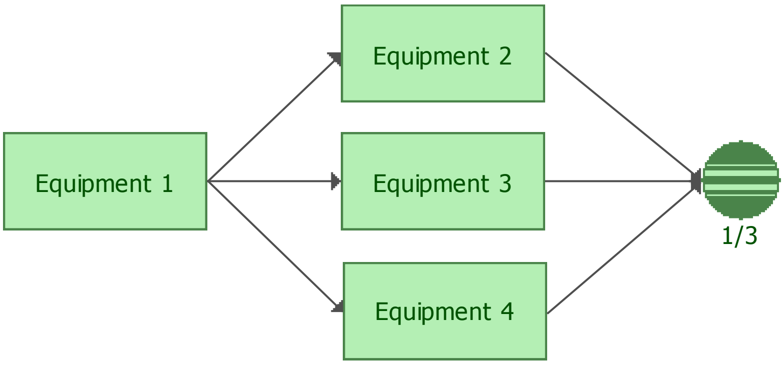


Figure 18 Three pieces of equipment in parallel and one piece of equipment in series configuration

Equation 1.11 is based on configuration 3:

$$R_S = [R_{\frac{1}{3}}\,(1 - \left(\left(1 - R_{eq2}\right)\left(1 - R_{eq3}\right)\left(1 - R_{eq4}\right)\right))]\,R_{eq1} \qquad (1.11)$$

$R_{1/3}$ depicts the 1 out of 3 node in the configuration.

Following are nine different scenarios that will be proposed and each of them has a specific outcome. The RBD for each scenario has four pieces of equipment with a specific configuration and different MTTF. For all the scenarios the MTTR was kept at a constant mean of 114 hours and a standard deviation of 11.4 hours. To calculate the 95% confidence interval a lot of simulation points are needed. Some of the scenarios simulation runs are too few to calculate the 95% confidence interval. The scenarios are described in Table 10. The simulation was run for 8000 years and 5000 simulation runs and the trend line for each diagram will also be added. The reason for a 8000 year simulation run is to see a trend on equipment that would fail once every 200 years. The more simulation runs the more correct your answer. Equation 1.12 shows trend line formula that will be used in all six scenarios.

$$y = mx + b \qquad (1.12)$$

Table 10 describes all the scenarios for each configuration that will be used.

Scenario	**Configuration**
1	200 Year MTTF - all 4 pieces of equipment in series
2	200 Year MTTF – 2 pieces of equipment in series, 2 pieces of equipment in parallel
3	200 Year MTTF – 1 piece of equipment in series, 3 pieces of equipment parallel
4	50 Year MTTF - all 4 pieces of equipment in series
5	50 Year MTTF - 2 pieces of equipment in series, 2 pieces of equipment in parallel
6	50 Year MTTF - 1 piece of equipment in series, 3 pieces of equipment parallel
7	10 Year MTTF - all 4 pieces of equipment in series
8	10 Year MTTF - 2 pieces of equipment in series, 2 pieces of equipment in parallel
9	10 Year MTTF - 1 piece of equipment in series, 3 pieces of equipment parallel

Table 10 Types of scenario testing MTTF

All 9 scenarios will be described in depth in Section 4.6.1 to 4.6.9

4.6.1 Scenario 1

Scenario 1 looks at a 200 year MTTF where all four pieces of equipment are in series.

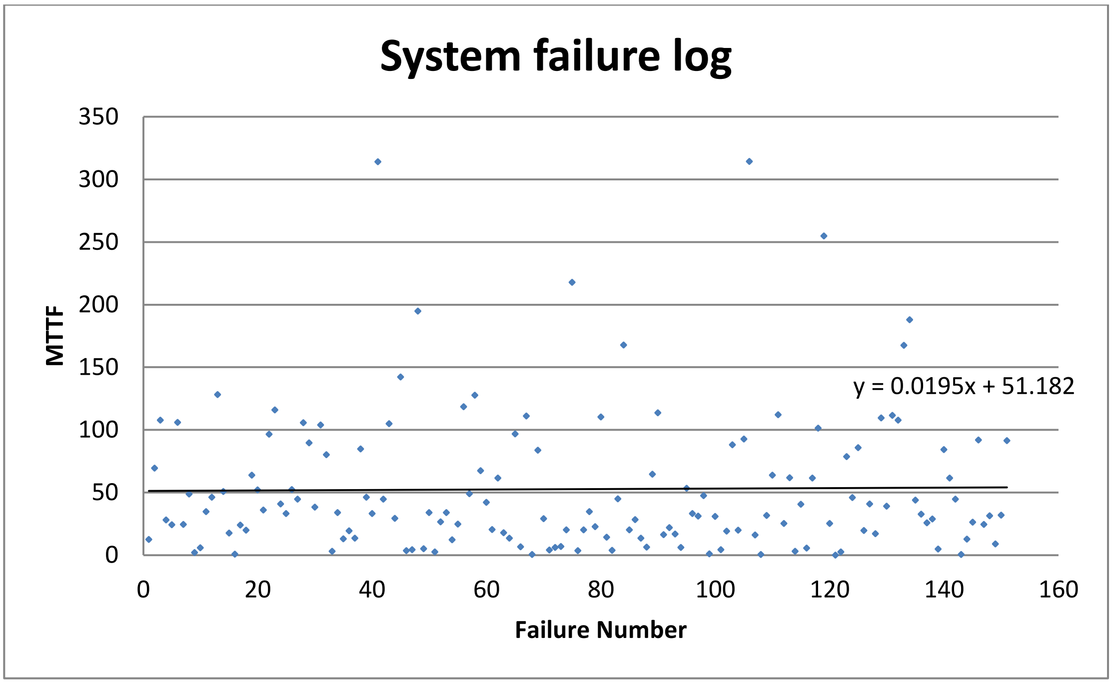


Figure 19 MTTF 200 years – all 4 pieces of equipment in series log

Scenario 1 is where all four pieces of equipment are in series. In other words, each one, when it fails, has an impact on the system. In this specific scenario, each piece of equipment will expect to fail once every 200 years. When running all four pieces of equipment in a simulation model, the model will expect to fail once every 50 years, because each piece of equipment has equal weight sharing. The trend line added to Figure 19 illustrates that point. The intercept need to be close to 50 years as shown by the equation below.

$$y = 0.0195x + 51.182 \qquad (1.13)$$

4.6.2 Scenario 2

Scenario 2 depicts two pieces of equipment in series and two pieces of equipment in parallel over a 200 year MTTF.

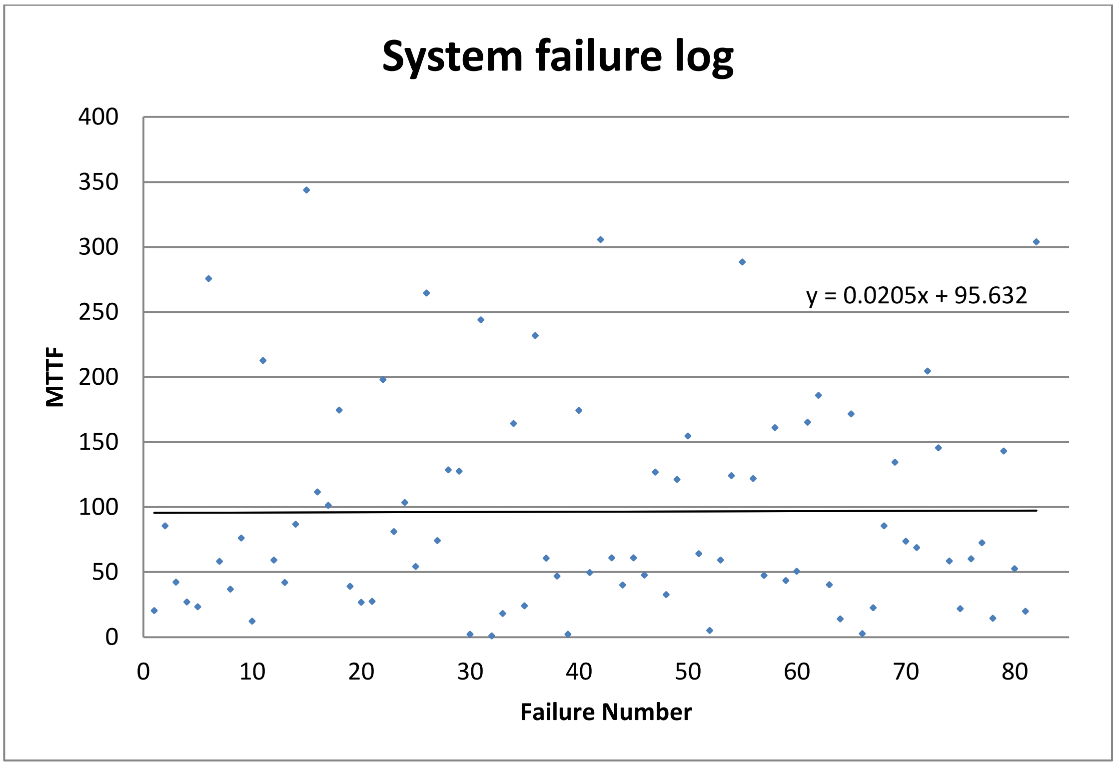


Figure 20 MTTF 200 years – two pieces of equipment in series, two pieces of equipment in parallel

Scenario 2 has two pieces of equipment in series and two in parallel. This would mean that the two pieces of equipment in parallel won't bring down the system and the two pieces of equipment that are in series will bring down the system. One will also have fewer failures because of the configuration. In this case, the trend line in Figure 20 shows that the average MTTF is close to 100 years.

$$y = 0.0205x + 95.632 \qquad (1.14)$$

4.6.3 Scenario 3

In this scenario, the configuration is three pieces of equipment in parallel and one in series.

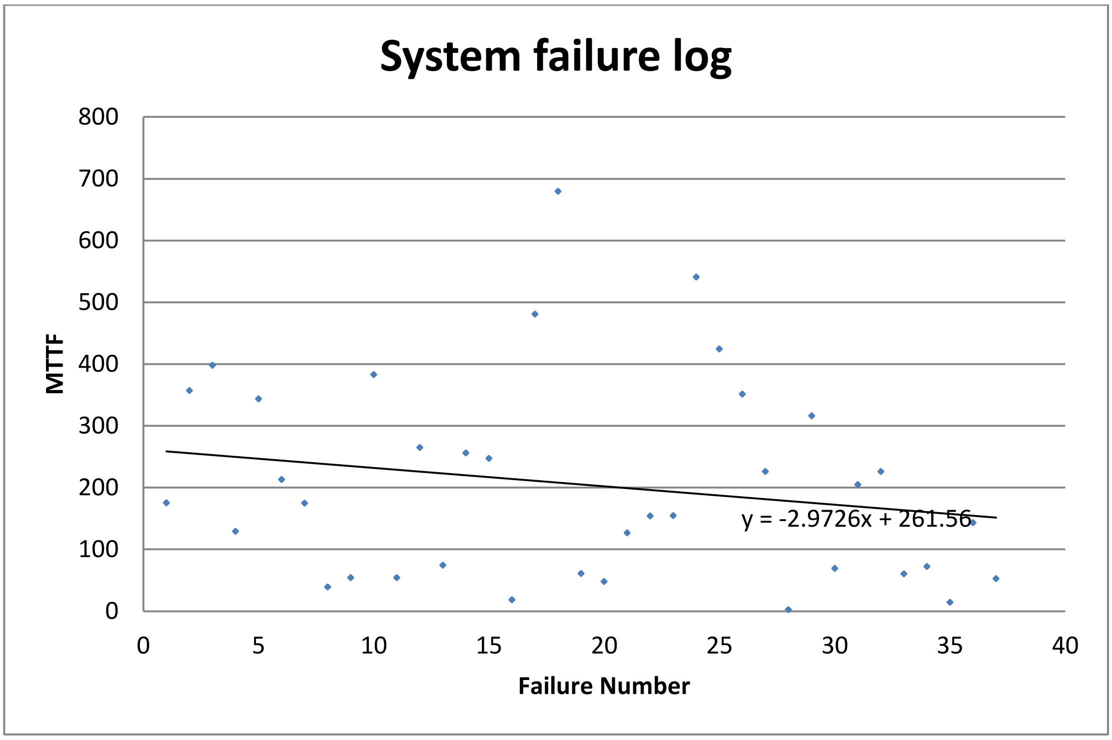


Figure 21 MTTF 200 years – three pieces of equipment in series, one piece of equipment in parallel

In Scenario three only one piece of equipment can fail over a 200 year MTTF. The other three pieces of equipment are in parallel and won't affect system availability. This means that running the model over an 8000 year period with only one piece of equipment that might fail; one would see fewer failures, a negative slope, as illustrated by the trend line added to Figure 21.

$$y = -2.97x + 261.56 \qquad (1.15)$$

4.6.4 Scenario 4

Scenario 4 has, like Scenario 1, the same configuration but with one difference. The MTTF for each piece of equipment is 50 years.

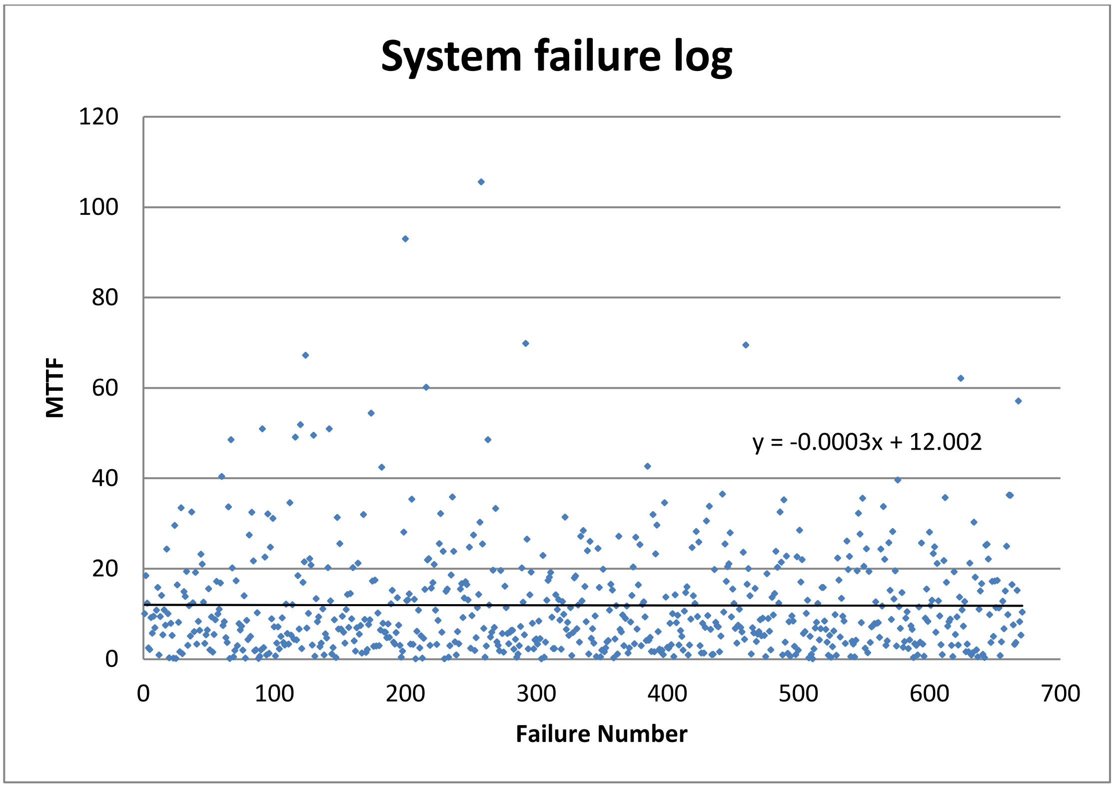


Figure 22 MTTF 50 years – all 4 pieces equipment in series

Scenario 4 will shows there are a lot of failures that happen because all four pieces of equipment has the ability to bring down the system. Over a 50 year period with four pieces of equipment in series, the trend line in Figure 22 shows that the average MTTF is close to 12.5 years.

$$y = -0.0003x + 12.002 \qquad (1.16)$$

4.6.5 Scenario 5

Scenario 5 has two pieces of equipment in series and two pieces of equipment in parallel with each piece of equipment having a MTTF of 50 years.

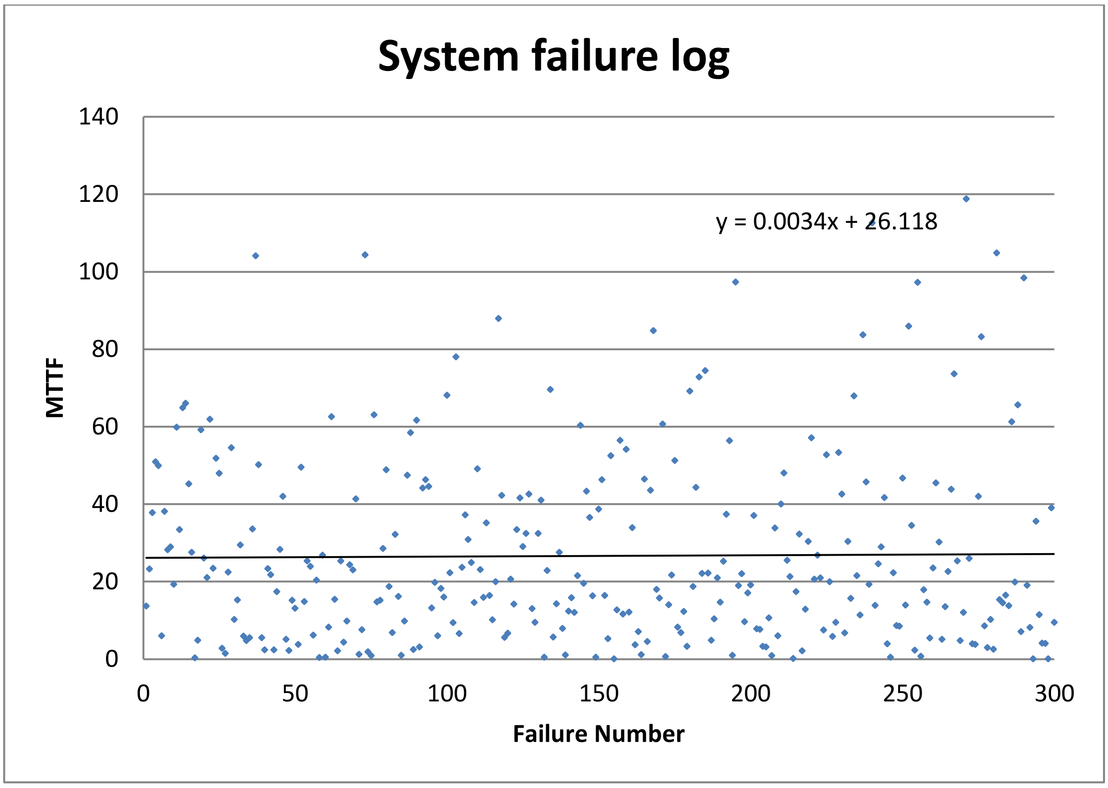


Figure 23 MTTF 50 years – two pieces of equipment in series, two pieces of equipment in parallel

The above scenario will have fewer failures than scenario 4 because only two pieces of equipment can switch off the system. With a MTTF of 50 years for each piece of equipment, the trend line in Figure 23 is averaged out at with a MTTF of close to 25 years.

$$y = 0.0034x + 26.118 \qquad (1.17)$$

4.6.6 Scenario 6

Scenario 6 is has three pieces of equipment in parallel and one piece of equipment in series with a MTTF for each piece of equipment at 50 years.

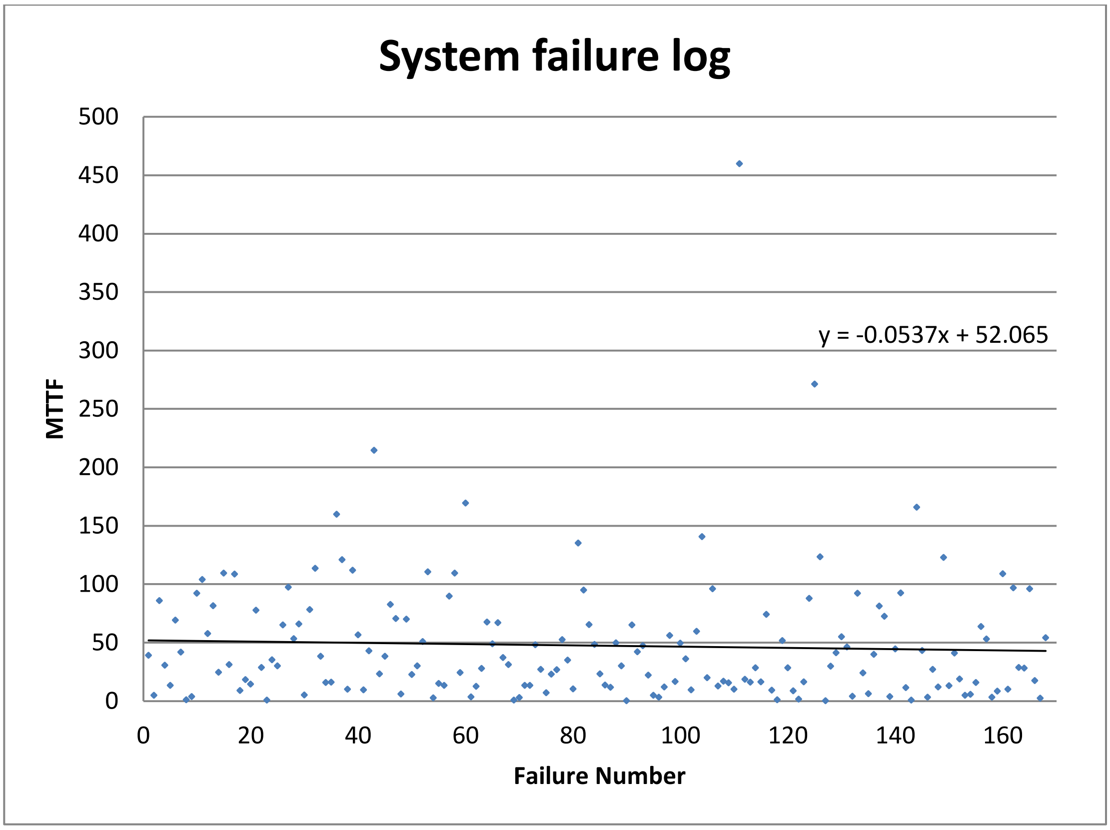


Figure 24 MTTF 50 years – three pieces of equipment in series, one piece of equipment in parallel

In scenario 6 there is only one piece of equipment that could switch the system off. One will have fewer failures because of only one piece of equipment that will have an impact on availability as evident by the trend line stabilising at more or less 50 years. The trend line in Figure 24 suggests the intercept is at 52.065 years.

$$y = -0.0537x + 52.065 \qquad (1.18)$$

4.6.7 Scenario 7

Scenario 7 has four pieces of equipment in series with each piece of equipment having a MTTF of 10 years.

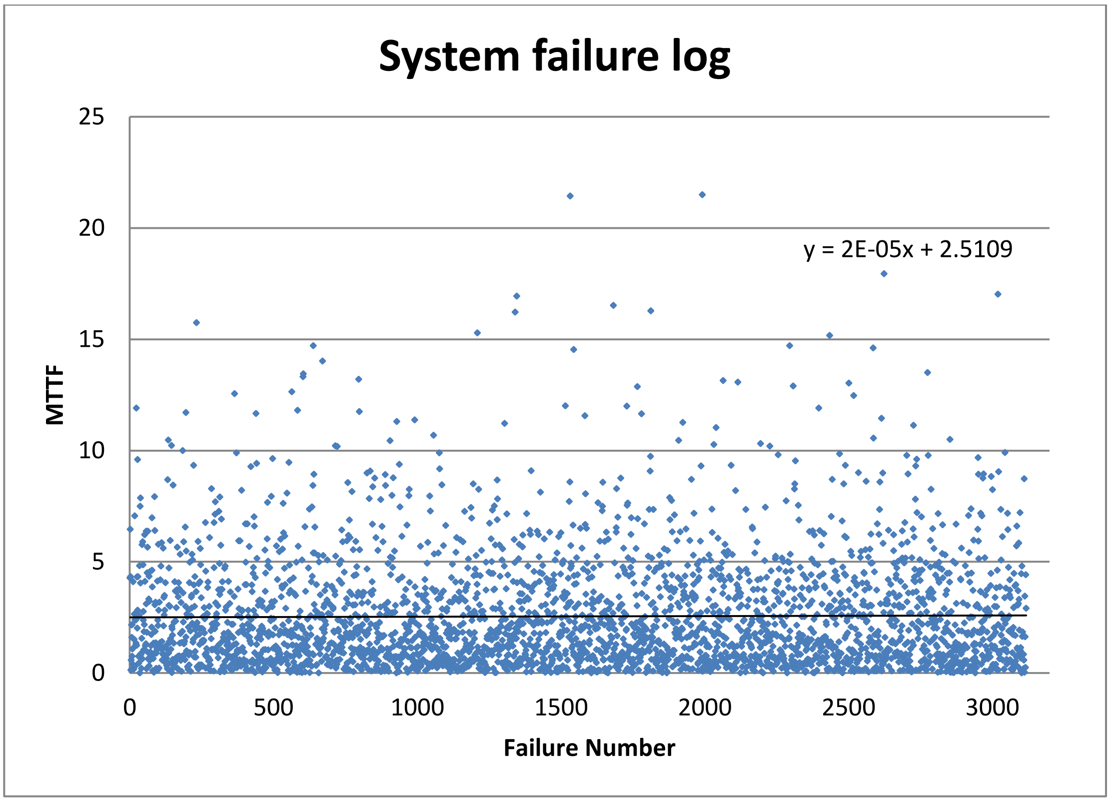


Figure 25 MTTF 10 years – all four pieces of equipment in series

Each piece of equipment has the potential to bring down the system. In this specific scenario, over an 8000 year simulation run, the system will go down every 2.5 years as shown by the trend line. This scenario shows the most failures out of all the scenarios. The more data there is the better fit the trend line will provide. The intercept in Figure 25 is 2.5 years.

$$y = 0.00002x + 2.5109 \qquad (1.19)$$

4.6.8 Scenario 8

Scenario 8 has two pieces of equipment in series and two pieces of equipment in parallel with a 10 year MTTF for each piece of equipment.

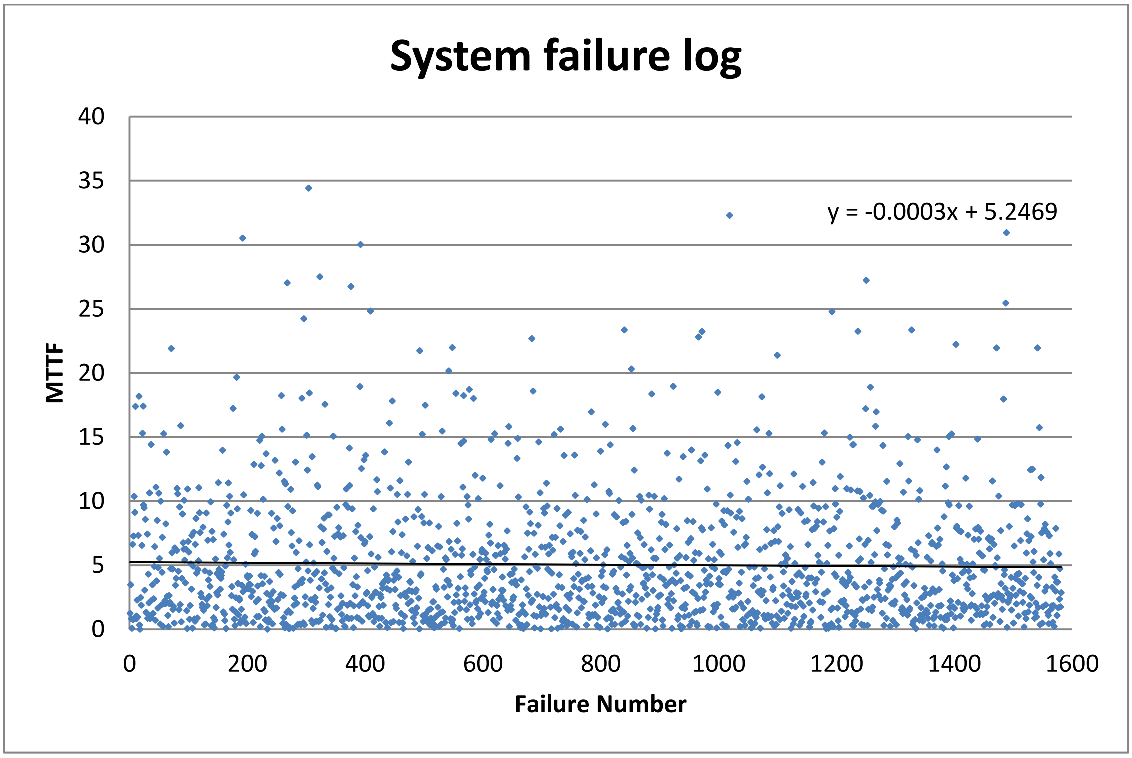


Figure 26 MTTF 10 years – 2 pieces of equipment in series, 2 pieces of equipment in parallel

Scenario 8 has fewer failures than scenario 7, because of its configuration. In Figure 26 the trend line is averaging out at 5 years as shown in equation 1.20, it is evidently that only two pieces of equipment in series will bring down the system.

$$y = -0.0003x + 5.2469 \qquad (1.20)$$

4.6.9 Scenario 9

Scenario 9 has three pieces of equipment in parallel and one piece of equipment in series with each piece of equipment having a 10 year MTTF.

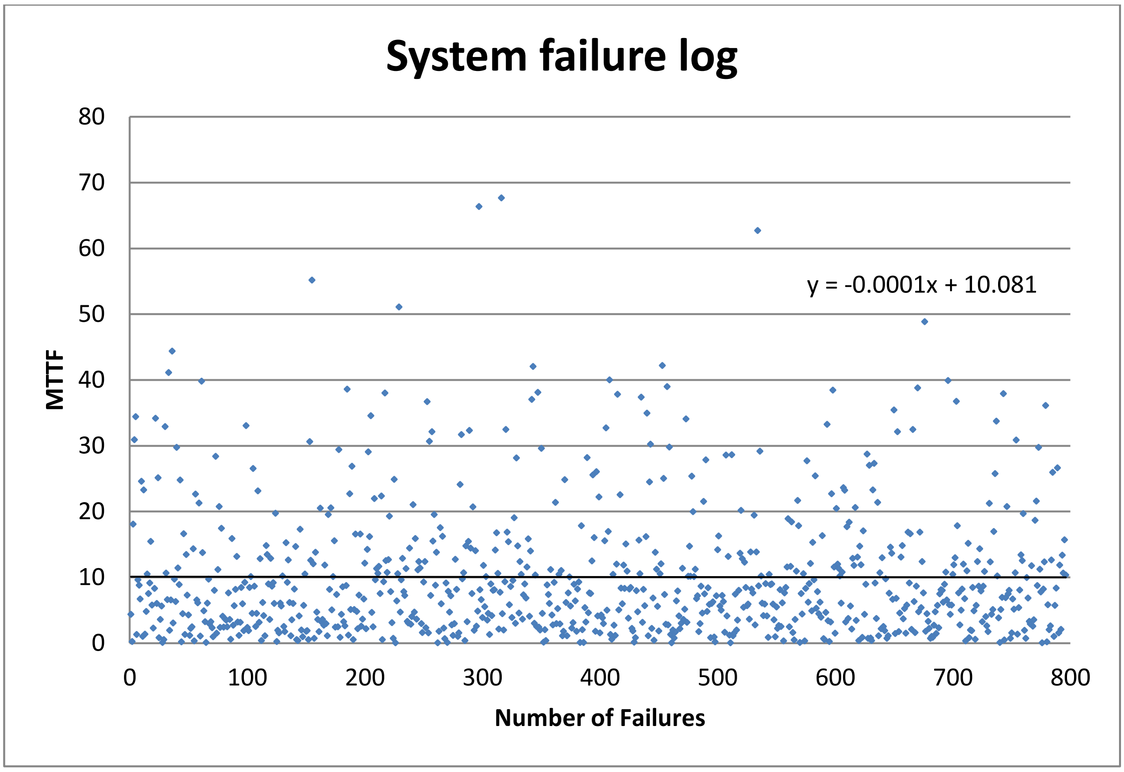


Figure 27 MTTF 10 years – three pieces of equipment in series, one piece of equipment in parallel

Scenario 9 has only one piece of equipment that could bring the system down. Because of the MTTF for each piece of equipment being 10 years and only one piece of equipment in series, one will have fewer failures, but enough for the simulation model to stabilise with a trend line of 10 years in Figure 27.

$$y = -0.0001x + 10.081 \qquad (1.21)$$

4.6.10 MTTF testing results

Table 11 below gives the output of the MTTF testing results.

Scenarios	Total amount of events	Availability	Unavailability	Equivalent days unavailable	Equivalent hours unavailable
1	151	99.97%	0.03%	0.11	2.63
2	82	99.98%	0.02%	0.07	1.75
3	37	99.99%	0.01%	0.04	0.88
4	671	99.90%	0.10%	0.38	9.11
5	300	99.95%	0.05%	0.19	4.56
6	168	99.97%	0.03%	0.09	2.28
7	3118	99.48%	0.52%	1.89	45.36
8	1551	99.74%	0.26%	0.95	22.75
9	796	99.87%	0.13%	0.47	11.39

Table 11 Types of scenario testing MTTF

When one compares the total failures to the availability, it is clear that all availability is high. The simulation run in scenario 7, 8 and 9 shows the lowest availability, but also has the highest failure number. The more failures there are, the higher the probability that the model's trend line will be stable as seen in the simulated runs in Figure 25, 26 and 27 in the previous section.

Figure 28 shows the total failures and availability relationship. The more failures one have the lower the availability will be.

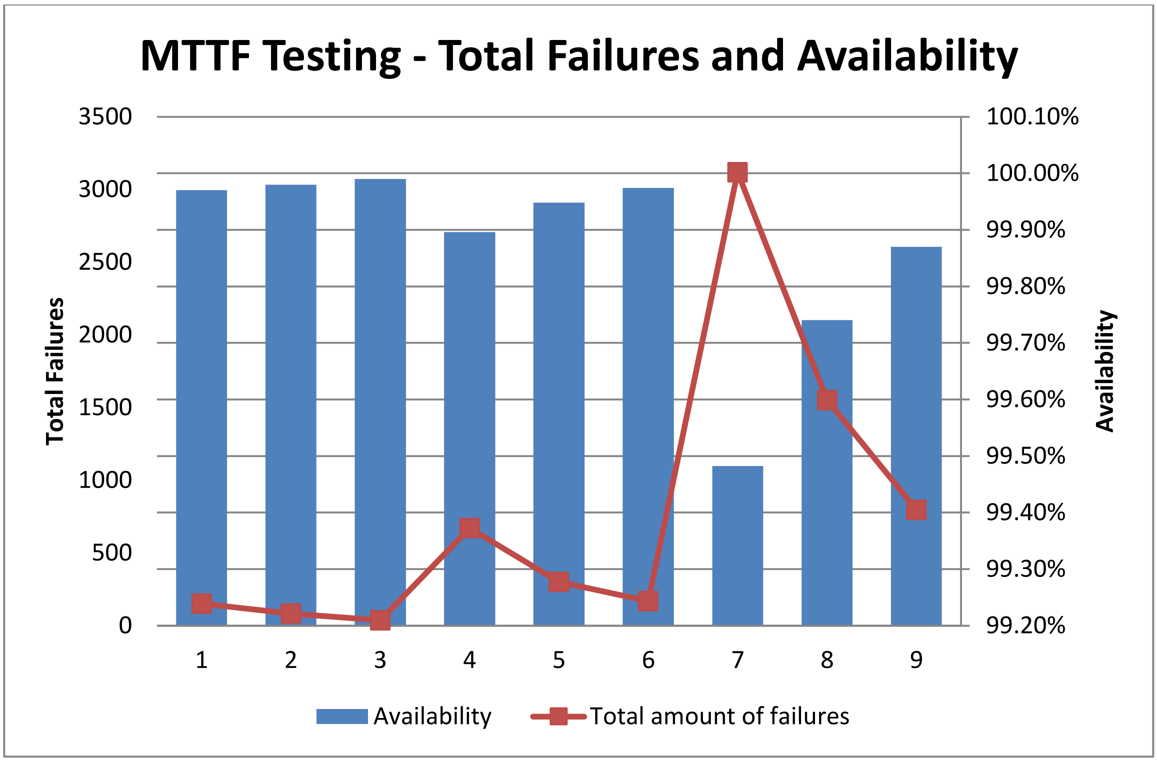


Figure 28 MTTF Testing – Total Failures and Availability relationship

Sensitivity analysis on MTTR reliability data is discussed in Section 4.7.

4.7 Sensitivity Analysis on MTTR Reliability data

Below are five different cases and each case having eleven scenarios. One piece of equipment was used for this sensitivity analysis experiment. In each case the MTTR stays the same while the MTTF in each scenario changes. What was illustrated in this sensitivity analysis is that the smaller the MTTR gets, in essence, the quicker your equipment is repaired and the higher your availability will be. All MTTR's will be modelled with a normal distribution and each MTTF will be modelled with an exponential distribution. The inherent availability will be given 8 digits after the decimal to show that the differences between scenarios are very small. The cases are described in each section below.

4.7.1 Case 1 – MTTR 24 hours

The MTTR stays the same at 24 hours for this case with each scenario has a different MTTF.

Scenarios	MTTF (hours)	MTTF (years)	MTTR (hours)	Inherent Availability
Scenario 1	2190	0.25	24	98.91598916%
Scenario 2	4380	0.5	24	99.45504087%
Scenario 3	8760	1	24	99.72677596%
Scenario 4	17520	2	24	99.86320109%
Scenario 5	35040	4	24	99.93155373%
Scenario 6	52560	6	24	99.95435874%
Scenario 7	70080	8	24	99.96576515%
Scenario 8	87600	10	24	99.97261024%
Scenario 9	131400	15	24	99.98173850%
Scenario 10	175200	20	24	99.98630325%
Scenario 11	262800	30	24	99.99086841%

Table 12 Case 1 MTTR 24hours

The MTTR for this case was at 24 hours. In essence this case should have the lowest availability for each scenario out of all the other cases. Equation 1.1 depicted in Chapter 1, will be used to calculate the availability in Table 12 A(t) is the availability of the function. The first scenario will be used as an example to show calculations.

$$A(t) = \frac{MTTF}{(MTTF + MTTR)}$$

$$A(t) = \frac{2190}{(2190 + 24)}$$

$$A(t) = 99.91598916\%$$

4.7.2 Case 2 – MTTR 12 hours

Case 2 the MTTR is 12 hours for all scenarios with each scenario having a different MTTF. MTTF units are expressed in hours and years.

Scenarios	MTTF (hours)	MTTF (years)	MTTR (hours)	Inherent Availability
Scenario 1	2190	0.25	12	99.45504087%
Scenario 2	4380	0.5	12	99.72677596%
Scenario 3	8760	1	12	99.86320109%
Scenario 4	17520	2	12	99.93155373%
Scenario 5	35040	4	12	99.96576515%
Scenario 6	52560	6	12	99.97717416%
Scenario 7	70080	8	12	99.98287964%
Scenario 8	87600	10	12	99.98630325%
Scenario 9	131400	15	12	99.99086841%
Scenario 10	175200	20	12	99.99315115%
Scenario 11	262800	30	12	99.99543400%

Table 13 Case 2 MTTR 12 hours

All scenarios in Table 13 have a higher availability than the previous case because equipment is repaired quicker. The calculation of the first scenario is as follow:

$$A(t) = \frac{MTTF}{(MTTF + MTTR)}$$

$$A(t) = \frac{2190}{(2190 + 12)}$$

$$A(t) = 99.45504087\%$$

4.7.3 Case 3 – MTTR 6 hours

Table 14 has MTTR at 6 hours for each scenario. MTTF units are expressed in hours and years.

Scenarios	MTTF (hours)	MTTF (years)	MTTR (hours)	Inherent Availability
Scenario 1	2190	0.25	6	99.72677596%
Scenario 2	4380	0.5	6	99.86320109%
Scenario 3	8760	1	6	99.93155373%
Scenario 4	17520	2	6	99.96576515%
Scenario 5	35040	4	6	99.98287964%
Scenario 6	52560	6	6	99.98858578%
Scenario 7	70080	8	6	99.99143909%
Scenario 8	87600	10	6	99.99315115%
Scenario 9	131400	15	6	99.99543400%
Scenario 10	175200	20	6	99.99657546%
Scenario 11	262800	30	6	99.99771695%

Table 14 Case 3 MTTR 6 hours

The MTTR has been halved from the previous case. In essence, equipment is being repaired at a quicker rate and availability has improved from the previous case. The calculation of the first scenario is as follow:

$$A(t) = \frac{MTTF}{(MTTF + MTTR)}$$

$$A(t) = \frac{2190}{(2190 + 6)}$$

$$A(t) = 99.72677596\%$$

4.7.4 Case 4 – MTTR 3 hours

Case 4 has an MTTR of 3 hours for each scenario. MTTF units are expressed in hours and years.

Scenarios	MTTF (hours)	MTTF (years)	MTTR (hours)	Inherent Availability
Scenario 1	2190	0.25	3	99.86320109%
Scenario 2	4380	0.5	3	99.93155373%
Scenario 3	8760	1	3	99.96576515%
Scenario 4	17520	2	3	99.98287964%
Scenario 5	35040	4	3	99.99143909%
Scenario 6	52560	6	3	99.99429256%
Scenario 7	70080	8	3	99.99571936%
Scenario 8	87600	10	3	99.99657546%
Scenario 9	131400	15	3	99.99771695%
Scenario 10	175200	20	3	99.99828770%
Scenario 11	262800	30	3	99.99885846%

Table 15 Case 4 MTTR 3 hours

Case 4, Table 15, has halved its MTTR from Case 3. The MTTR for this exercise is at 3 hours for each scenario. The availability is higher than in Case 3. The calculation of the first scenario is as follow:

$$A(t) = \frac{MTTF}{(MTTF + MTTR)}$$

$$A(t) = \frac{2190}{(2190 + 3)}$$

$$A(t) = 99.86320109\%$$

4.7.5 Case 5 – MTTR 0.5 hours

Case 5 has an MTTR of 0.5 hours for each scenario. MTTF units are expressed in hours and years.

Scenarios	MTTF (hours)	MTTF (years)	MTTR (hours)	Inherent Availability
Scenario 1	2190	0.25	0.5	99.97717416%
Scenario 2	4380	0.5	0.5	99.98858578%
Scenario 3	8760	1	0.5	99.99429256%
Scenario 4	17520	2	0.5	99.99714620%
Scenario 5	35040	4	0.5	99.99857308%
Scenario 6	52560	6	0.5	99.99904872%
Scenario 7	70080	8	0.5	99.99928653%
Scenario 8	87600	10	0.5	99.99942923%
Scenario 9	131400	15	0.5	99.99961948%
Scenario 10	175200	20	0.5	99.99971461%
Scenario 11	262800	30	0.5	99.99980974%

Table 16 Case 5 MTTR 0.5 hours

Table 16 illustrates that Case 5 has the highest availability out of all the tested cases. The MTTR is 0.5 hours which means that the equipment gets repaired very quickly which in essence have a very high availability. The calculation of the first scenario is as follow:

$$A(t) = \frac{MTTF}{(MTTF + MTTR)}$$

$$A(t) = \frac{2190}{(2190 + 0.5)}$$

$$A(t) = 99.97717416\%$$

4.7.6 Results of MTTR impact on availability

All 5 cases where the MTTR impact on availability are shown in Figure 29 below.

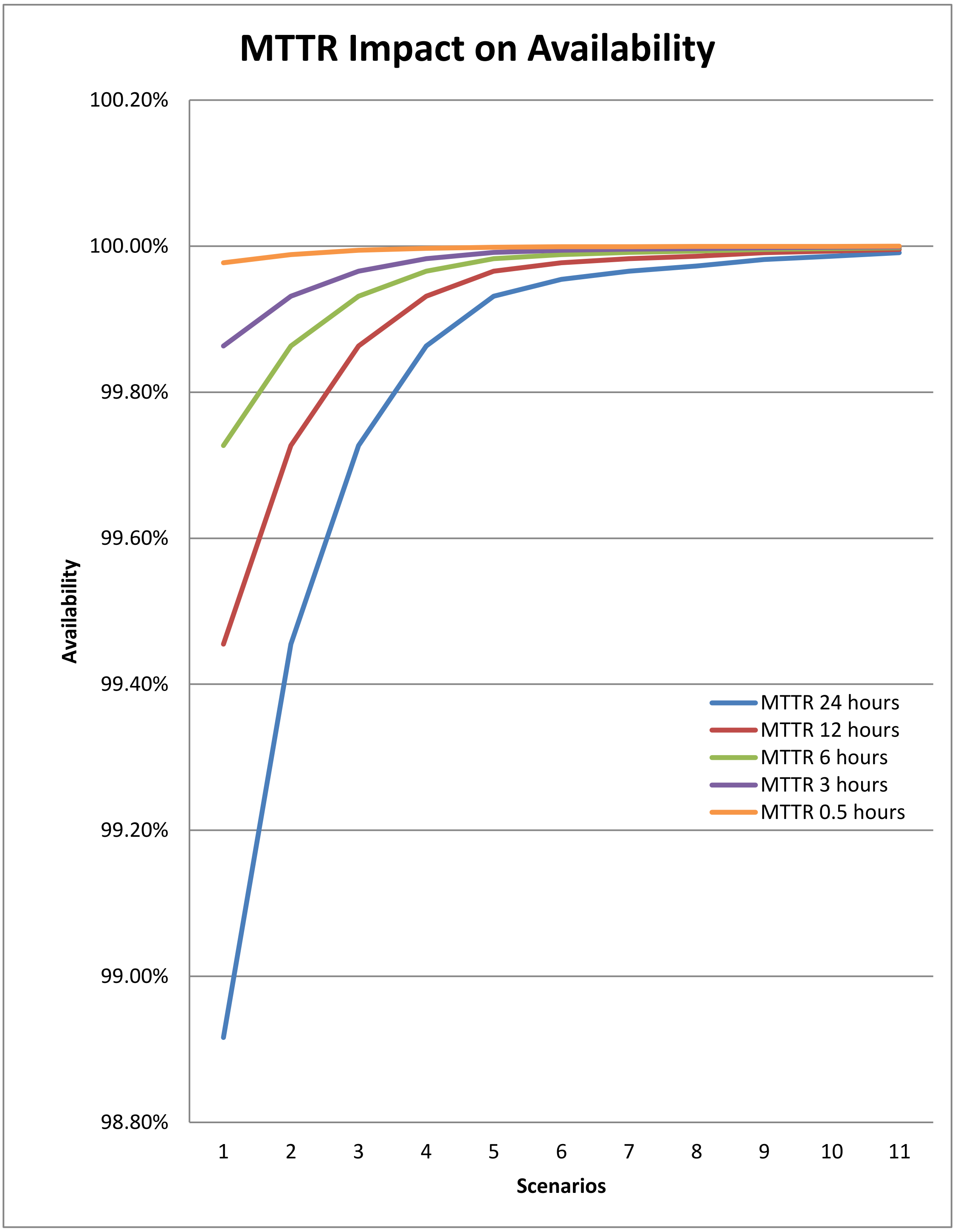


Figure 29 MTTR impact on Availability

Figure 29 shows the impact of all five cases on availability. The MTTF for each scenario stayed the same for every case. The MTTR for every case has changed as well to see the impact of a stabilised MTTR on equipment that would fail at different times.

The results are conclusive in saying that the quicker equipment gets repaired, the higher the availability of a system, and the higher the production efficiency number.

Section 4.8 is defining sensitivity analysis on production efficiency.

4.8 Sensitivity Analysis on Production Efficiency

Sensitivity analysis on production efficiency will be looked at in depth. The raw data in Table 17 and 18 consists of facility data of the last 27 years, where market volume, availability, production volume and production efficiency are tabled. Correlation is calculated and defined in the next sub section. Correlation and regression analysis will be used to calculate the delta between production efficiency in combination with RAM and production efficiency when RAM is detached. The sum of squared errors (SSE) will also be used to see what the difference in error is between production efficiency and the regression calculated.

The bathtub curve analysis is defined in three segments:

a. Start of life, equation 1.22

$$X \leq X_1 \qquad (1.22)$$

Where the regression analysis is:
$y = A\ e^{B(X-X_0)} + C$

A = Production efficiency at X_0;

B = Slope;

C = Constant variable;

e = Exponential function;

X_0 = 1990; and

X_1 = 1996;

b. Steady state, equation 1.23

$$X_1 \leq X \leq X_2 \qquad (1.23)$$

Where the regression analysis is:

C = Constant variable;

X_1 = 1997; and

X_2 = 2012;

c. End of life, equation 1.24

$$X_2 > X \qquad (1.24)$$

Where the regression analysis is:

$y = A\, e^{B(X-X_2)} + C$

A = Production efficiency at X_0;

B = Slope;

C = Constant variable;

e = Exponential function;

X_3 = 2017; and

X_2 = 2012;

The equation for SSE is:

$$SSE = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \qquad (1.25)$$

Where;

y_i = Actual

$\hat{y}_i$ = Prediction

To calculate the benefit of RAM (BRAM) of the delta volume, showcased in Section 4.8.3, the following equation will be used:

$$\text{BRAM} = \int_{x_0}^{x_1}(Y_{With\ RAM} - Y_{Without\ RAM})dx + \int_{x_1}^{x_2}(Y_{With\ RAM} - Y_{Without\ RAM})dx + \int_{x_2}^{x_3}(Y_{With\ RAM} - Y_{Without\ RAM})dx \qquad (1.26)$$

4.8.1 Correlation in Production Efficiency

Correlation will be used to see if there is a mutual relationship between production efficiency and RAM in the following two cases:

- Production efficiency calculated with RAM; and
- Production efficiency calculated without RAM.

Regression analysis will test this outcome of production efficiency in Section 4.8.2 and 4.8.3.

The SSE will be used to see how big the error is between production efficiency and the regression, also calculated in the raw data sheet in the next sections.

4.8.2 Production Efficiency calculated with RAM

Below in Table 17 is the raw data of a facility where the market volume in consistent 100%. The maximum that could be produced is 400m³.The availability calculated takes an in-depth look at equipment and how it interacts with other pieces of equipment in an overall system. The market volume is constant at 100%.

Date	Market Volume %	Availability % (with RAM)	Production m³	Production Efficiency %	Regression	SSE
1990	100%	96.75%	387	96.75%	96.95%	4.1E-06
1991	100%	97.50%	390	97.50%	97.43%	5.0E-07
1992	100%	98.00%	392	98.00%	97.91%	8.5E-07
1993	100%	98.50%	394	98.50%	98.39%	1.3E-06
1994	100%	99.00%	396	99.00%	98.87%	1.7E-06
1995	100%	99.25%	397	99.25%	99.36%	1.1E-06
1996	100%	99.75%	399	99.75%	99.84%	8.8E-07
1997	100%	99.80%	399.2	99.80%	99.89%	7.6E-07
1998	100%	99.85%	399.4	99.85%	99.89%	1.4E-07
1999	100%	99.90%	399.6	99.90%	99.89%	1.6E-08
2000	100%	99.91%	399.64	99.91%	99.89%	5.1E-08
2001	100%	99.92%	399.68	99.92%	99.89%	1.1E-07
2002	100%	99.93%	399.72	99.93%	99.89%	1.8E-07
2003	100%	99.94%	399.76	99.94%	99.89%	2.8E-07
2004	100%	99.95%	399.8	99.95%	99.89%	3.9E-07
2005	100%	99.94%	399.76	99.94%	99.89%	2.8E-07
2006	100%	99.93%	399.72	99.93%	99.89%	1.8E-07
2007	100%	99.92%	399.68	99.92%	99.89%	1.1E-07
2008	100%	99.91%	399.64	99.91%	99.89%	5.1E-08
2009	100%	99.90%	399.6	99.90%	99.89%	1.6E-08
2010	100%	99.85%	399.4	99.85%	99.89%	1.4E-07
2011	100%	99.80%	399.2	99.80%	99.89%	7.6E-07
2012	100%	99.75%	399	99.75%	99.89%	1.9E-06
2013	100%	99.00%	396	99.00%	98.95%	2.1E-07
2014	100%	98.25%	393	98.25%	98.32%	5.3E-07
2015	100%	97.75%	391	97.75%	97.70%	2.9E-07
2016	100%	97.00%	388	97.00%	97.07%	5.3E-07
2017	100%	96.50%	386	96.50%	96.45%	2.1E-07
Sum						1.7554E-05

Table 17 Raw data for production efficiency calculated with RAM

The following segments of the bathtub curve analysis is:

a. Start of life:

$$y = A\, e^{-B(X-X_0)} + C$$

A = 96.75%, where production efficiency at X_0;

B = 0.004906;

C = 0.02036;

X_0 = 1990; and

X_1 = 1996.

b. Steady state:

C = 0.998874;

X_1 = 1997; and

X_2 = 2012.

c. End of life:

$$y = A\, e^{-B(X-X_0)} + C$$

A = 99.75%, where production efficiency at X_2;

B = -0.00644;

C = 0.005896;

X_3 = 2017; and

X_2 = 2012.

The R-square calculated for production efficiency with RAM is 0.994806

4.8.3 Production Efficiency calculated without RAM

Raw data where production efficiency is calculated with an overall availability is shown in Table 18. Overall availability is calculated by saying that the plant was available for x amount of days per year.

Date	Market Volume %	Availability % (Without RAM)	Production m³	Production Efficiency %	Regression	SSE
1990	100%	96.23%	384.91	96.23%	96.38%	2.17E-06
1991	100%	97.05%	388.20	97.05%	96.83%	4.72E-06
1992	100%	97.49%	389.96	97.49%	97.29%	3.88E-06
1993	100%	97.52%	390.10	97.52%	97.75%	5.29E-06
1994	100%	98.07%	392.30	98.07%	98.22%	2.05E-06
1995	100%	98.67%	394.69	98.67%	98.68%	1.41E-08
1996	100%	99.27%	397.08	99.27%	99.15%	1.39E-06
1997	100%	98.86%	395.42	98.86%	99.17%	1.01E-05
1998	100%	98.97%	395.86	98.97%	99.17%	4.33E-06
1999	100%	99.17%	396.68	99.17%	99.17%	1.03E-09
2000	100%	98.99%	395.96	98.99%	99.17%	3.35E-06
2001	100%	98.99%	395.96	98.99%	99.17%	3.33E-06
2002	100%	99.49%	397.96	99.49%	99.17%	1.00E-05
2003	100%	99.04%	396.17	99.04%	99.17%	1.73E-06
2004	100%	99.51%	398.03	99.51%	99.17%	1.11E-05
2005	100%	99.55%	398.20	99.55%	99.17%	1.42E-05
2006	100%	99.90%	399.60	99.90%	99.17%	5.26E-05
2007	100%	98.95%	395.79	98.95%	99.17%	5.11E-06
2008	100%	99.04%	396.14	99.04%	99.17%	1.89E-06
2009	100%	99.42%	397.67	99.42%	99.17%	5.95E-06
2010	100%	99.10%	396.42	99.10%	99.17%	4.76E-07
2011	100%	98.82%	395.29	98.82%	99.17%	1.24E-05
2012	100%	98.99%	395.96	98.99%	99.17%	3.39E-06
2013	100%	98.01%	392.05	98.01%	98.04%	5.99E-08
2014	100%	97.78%	391.11	97.78%	97.57%	4.27E-06
2015	100%	96.94%	387.74	96.94%	97.11%	2.93E-06
2016	100%	96.46%	385.85	96.46%	96.64%	3.34E-06
2017	100%	96.36%	385.42	96.36%	96.18%	2.95E-06
Sum						1.73E-04

Table 18 Raw data for production efficiency calculated without RAM

The bathtub curve analysis for this section is:

a. Start of life:

$$y = A\,e^{-B(X-X_0)} + C$$

A = 96.23%, where production efficiency at X_0;

B = 0.004741;

C = 0.001473;

X_0 = 1990; and

X_1 = 1996.

b. Steady state:

C = 0.991736

X_1 = 1996; and

X_2 = 2012.

c. End of life:

$$y = A\,e^{-B(X-X_2)} + C$$

A = 98.99%, where production efficiency at X_2;

B = -0.00479;

C = 0.004933;

X_3 = 2017; and

X_2 = 2012.

The R-square calculated for production efficiency without RAM is 0.943418

4.8.4 Benefit of RAM

The benefit of RAM (BRAM) proofs that when RAM modelling added to a volumetric based system that the answer is more aligned with current production. The losses that occur when not using RAM is too big not to do anything about. The following calculations describes the BRAM in a volumetric facility based on the example of Section 4.8:

$$\mathrm{BRAM} = \int_{x_0}^{x_1}(Y_{\mathrm{With\ RAM}} - Y_{\mathrm{Without\ RAM}})dx + \int_{x_1}^{x_2}(Y_{\mathrm{With\ RAM}} - Y_{\mathrm{Without\ RAM}})dx + \int_{x_2}^{x_3}(Y_{\mathrm{With\ RAM}} - Y_{\mathrm{Without\ RAM}})dx$$

$$\mathrm{BRAM} = \int_{1990}^{1996}\left(0.9675e^{0.004906(x-1990)} + 0.002036 - 0.9623e^{0.004741(x-1990)}\right)dx + \int_{1996}^{2012}(0.998874 - 0.991736)dx + \int_{2012}^{2017}\left(0.9975e^{-0.00639(x-2012)} - 0.00161 - 0.9899e^{-0.00475(x-2017)}\right)dx$$

$\mathrm{BRAM} =$ 18.82%

The 18.82% BRAM calculated also means that the production volume for the last 27 years gained 75.28m³ in total. Figure 30 shows the delta between production efficiency with RAM modelling and production efficiency without RAM modelling. Where RAM modelling is added, better results are produced that is in line with current production.

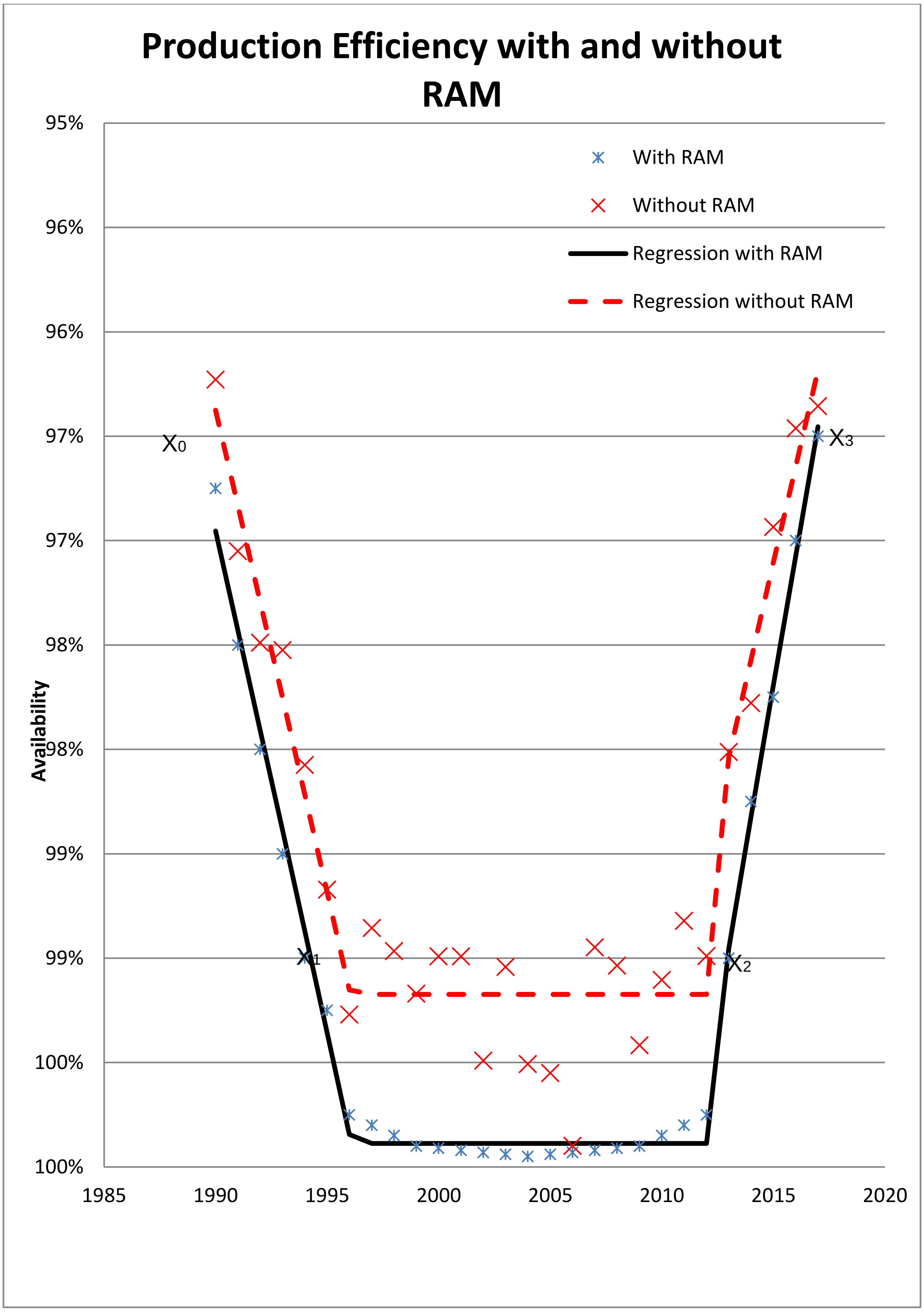


Figure 30 Production efficiency with and without RAM

Section 4.9 explains stochastic simulation and production efficiency results.

4.9 **Stochastic Simulation and Production Efficiency Results**

Production efficiency is determined with a high-level stochastic simulation model and used to predict and analyse the throughput estimate for the facility design.

Arena® is a discrete event simulation modelling tool used to predict the system-wide impact of operating rules and alternatives including reduced capacity during failures or phased shutdowns, ramp-up as well as the impact of buffers. The model runs in hourly intervals with a simulation length of 8 years and for 5000 repetitions.

This simulation model uses failures from the results of the RAM model as input.

The production efficiency model considers the following:

- Reduced rates as a result of failures;
- Ramp-up time and shutdown time;
- Impacts of tanks;
- Planned shutdowns; and
- Operating rules (alternative flow during failures):
    - If a unit or sub-system is shut down, can feed be rerouted to an alternate destination?
    - What backup volume is available for downstream facilities?
    - Are there recycle options to keep the unit online?; and
    - What shuts down first and under what conditions?

A base simulation model was developed. Scenarios were created on this base model where a portion of the model was deactivated or removed. For example, the restart times after a breakdown were removed to indicate the impact of the restart times on the production efficiency. In the first case the restart times after a breakdown were removed as well as the tank constraints in the model and the planned shutdowns and ramp-up times of the units after a planned shutdown. In the next case the restart times after a breakdown are activated. In the following case the tank constraints in the model are activated. In the case thereafter planned shutdowns in the model are activated. With the activation of the restart times after a shutdown in the following case the model has all the deactivated parts on.

The following list shows the order in the cases was run:

- Only breakdowns activated;
- Add the restart times after a breakdown;
- Add the tank constraints in the model;
- Add planned shutdowns; and
- Add ramp-up times after a shutdown.

This phased approach was used to show the percentage reduction that each had on the production efficiency. Due to the interactive nature of the facility the cases could be interpreted in isolation. For example, with shutdowns added there are less time available for the units to break down; thus, the units break less than in the breakdowns only scenario. The following table shows the production efficiency of each case and the delta reduction in production efficiency.

Table 19 shows the production efficiency of each scenario and the delta reduction in production efficiency. The maximum average production efficiency that can be achieved under the current assumptions and availabilities is 88.54%.

Scenario	**Production Efficiency (%)**	**Delta reduction (%)**
Failures – RAM results	96	4.0
Add unit restart times	95.5	0.5
Add tanks	95.25	0.25
Add planned shutdowns	89.5	5.75
Add unit ramp up times after shutdown	88.54	0.96

Table 19 The production efficiency of the different scenarios

Note 1. Reduction starts from 100%

Figure 31 shows the production efficiency of each simulation run for the shutdown scenario. This shows the spread of production efficiency values generated by the simulation. The average production efficiency is shown as a red line on the Figure. If one would calculate a 95% production efficiency confidence interval, it will be between 88.47% and 88.62%. The confidence interval was calculated for a population mean, using a normal distribution.

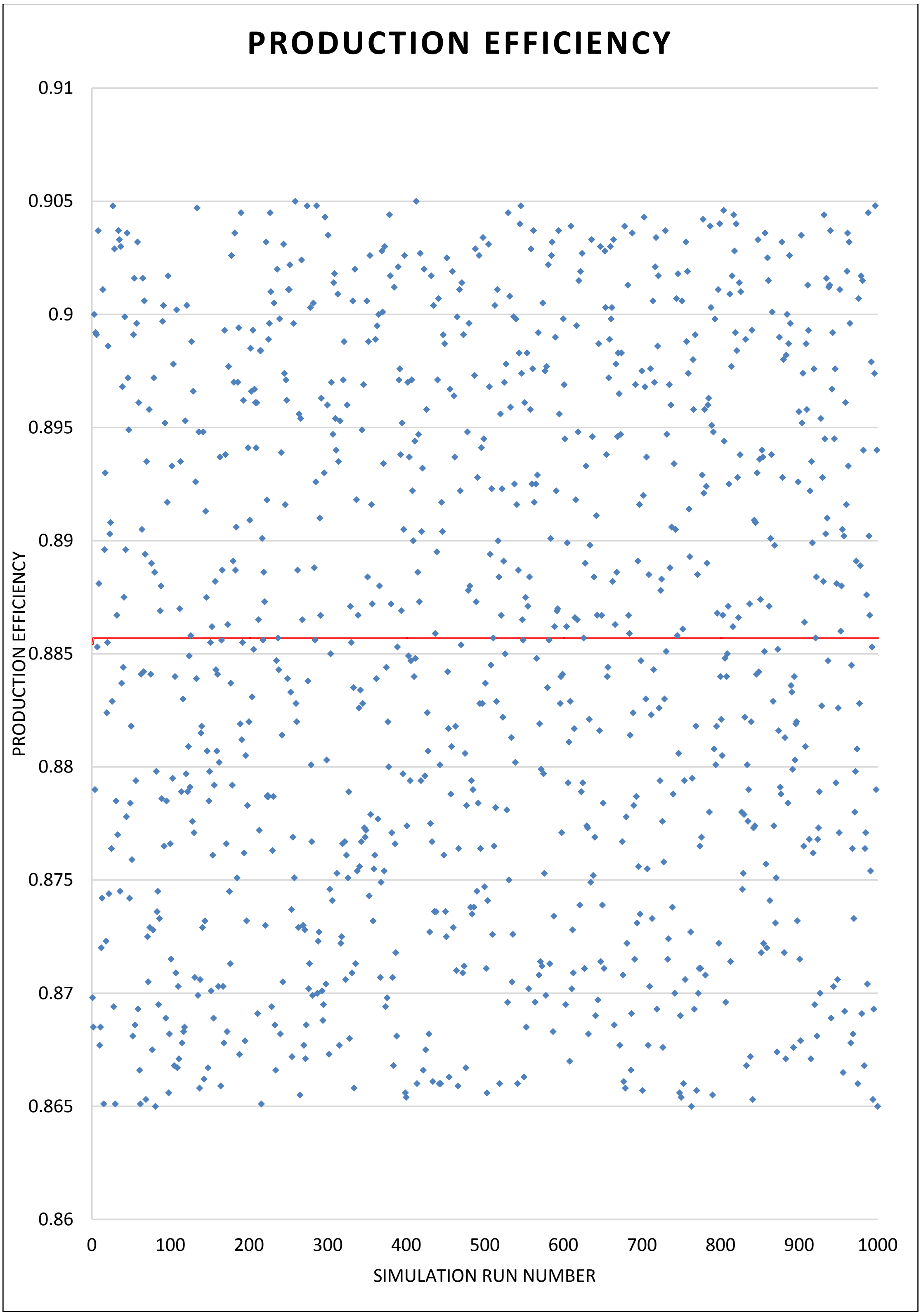


Figure 31 Diagram of the tank average level as a percentage of time

Production efficiency model conclusions contextualised in Section 4.10.

4.10 **Production Efficiency model conclusions**

The RAM model determines the availability of the facility and provides input into the production efficiency model. The production efficiency model is a high level stochastic simulation model of the facility and determines the production efficiency of the facility based on the availability of the units, the sizes of the tank and the operating rules.

The average production efficiency of the facility is 88.54% and the shutdowns provide the biggest reduction in production efficiency of 5.75%. The sizes of the tanks are responsible for an average reduction of 0.25% in the production line. The size of the tank is interconnected with other tanks in the facility; increasing the size of one tank will shift the bottleneck to other areas of the facility.

Table 20 reflects 8 years of planned maintenance or shutdowns built into the model. Every second year the shutdown period in the oil and gas industry changes due to the law. The reason for this is environmental legislation. Legislation states that large equipment needs to be maintained as well. It takes 25 days to do maintenance on these large vessels.

Year after start up	Days shutdown
1	2
2	25
3	2
4	25
5	2
6	25
7	2
8	25

Table 20 Planned shutdown duration in days

CHAPTER 5 RESULTS AND DISCUSSION

5.1 Research Results

The main purpose when developing a RAM model is to analyse the RAM features which can be used as the foundation for the analysis of the reliability data (Jackson, et al., 2005). Reliability data contains failure and repair data. Together with the RAM model, a stochastic simulation model was developed to see what effect the failure and repair data would have on production efficiency.

“A conceptual model was developed in Chapter 4 and showed how an appropriate maintenance strategy could be identified based on RAM analysis. The first step for selection of a better maintenance strategy for each component or sub-system is to find its failure rate based on available data from the maintenance reports, failure observations, daily reports, etc.

The concept of importance measures was developed and some importance measures were defined to manage the efforts to improve availability of the system. The availability of a repairable system can be improved by reducing the failure rate or increasing the repair rate of each component. In other words, one needs to find a way to increase the MTTF and decrease the MTTR of a piece of equipment or a system (Calixto, 2016).” When the MTTF increases and the MTTR decrease the production efficiency increases.

The discussion is defined in Section 5.2.

5.2 **Discussion**

5.2.1 RAM improvement

To improve the production efficiency number by not only adding equipment to the model but also better results going to the production facility by using a RAM study is the intention of this thesis (see the case study in chapter 4). By doing this, ways to improve production efficiency will become clear. The main requirements for the operation of large and composite systems are typically stated in terms of cost and availability and of equipment reliability, or equally in terms of overall operational time and of overall downtime.

Once the reliability of equipment improves, the throughput of a facility increases and evidently, the production efficiency increases. This theory is illustrated in the case study provided.

These requirements have then to be taken into consideration when the system design stage is in review in order to decide the suitable reliability and availability of each of its pieces of equipment and systems. A slight improvement in the system's reliability and availability is directly related to extra effort from maintenance personnel (Adhikary, et al., 2012). Therefore, it is very important to grow and breed new techniques for reliability and availability equipment and systems with minimum effort as seen in the case study.

The availability and reliability of equipment is a good assessment criterion of a system’s performance. Availability and reliability values depend on the system’s structure and equipment (Jackson, et al., 2005). “*These values decrease as the equipment’s’ age increase, i.e. their allocated times are influenced by their interaction with one another, the applied maintenance philosophies and their environments* (National Acadamy of Sciences, 2010).”

A couple of methods to improve the availability of a repairable system, namely:

- Increase mean time to fails, or in other words, reduce the failure rate of equipment; and
- Improve the mean time to repair of equipment, or, which also means, reduce the downtime of equipment by repairing it quicker.

5.2.2 The concept of equipment importance measures

The idea of importance measures came from the observation that in any orderly arrangement of equipment in a system, some of the equipment is more significant than others for providing certain system characteristics (Calixto, 2016). According to Goel (2004:116) “*equipment importance analysis is the crux of the overall system reliability quantification development which allows the areas of the system, which contribute most to the downtime, to be recognised and indicates changes which will improve the system’s reliability*. (Goel, 2004)“

To improve reliability of a system, efforts need to be focused on the equipment whom contributes the most to downtime, by upgrading that equipment with the biggest enhancement in overall reliability is achievable. Reliability and availability importance measures allocate numerical values between 0 and 1 to each piece of equipment; 1 meaning it indicates the maximum level of importance.

“*However, importance measures do not communicate everything about how equipment affects the system’s reliability and availability. To be more specific, they only give some information about how equipment reliability and availability affect one another* (Wang, 2012).”

5.2.3 Significance to a South African manufacturing chemical company

A Reliability, Availability and Maintainability (RAM) study is an important part of the basic engineering process. A world leading manufacturing company simulation modelling team saw an opportunity to use stochastic simulation in combination with RAM models to meet the challenge of determining the reliability and production efficiency of new and existing facilities. This approach also allowed additional dynamic factors to be considered in the RAM analysis such as ramp-up and ramp-down rates, upstream and downstream upsets and storage.

The simulation modelling team built RAM and production efficiency models for this manufacturing company’s current and future use. These types of models allow testing of alternative maintenance strategies and identification of priority equipment to maintain a high level of availability at sustained production rates. The models also assist with the design of new facilities to reach a specific availability and production efficiency at the lowest cost with no excessive equipment or sparing.

One of the recommendations, based on model results, was to add a redundant centrifugal pump, at a cost of R1.5 million. This would eliminate the bottleneck of having to shut down the facility thereby, increasing the production efficiency and resulting in a value addition of R12 million and more per annum.

RAM models deems highly efficient for existing facilities e.g. one of this manufacturing company's facilities was able to attribute more than R100 million of savings in production losses due to the redundancy on the Un-Interruptible Power Supply (UPS) units. The root cause of the original failures was that the UPS did not switch on quick enough to prevent a plant shutdown due to the configuration of the internal equipment. The scenarios evaluated ways to improve system availability by considering both equipment failures and maintenance factors. The results show where the biggest benefit lie and it helps with decision making for possible systems upgrades that increase system efficiency and subsequently system online time. The study identified the most critical spares ranking equipment from highest to lowest priority. The study also contributed to the decision making with regards to new installations, to anticipated renewals and for areas where higher availability was required.

These are only two examples, however, RAM is used extensively and every project yields real value to the business. Due to the value of this modelling, business in South Africa and in the world is willing to pay millions for these studies to be done on engineering and in-house projects. Adding the production efficiency answer to the modelling yields a highly reliable throughput answer that can be used in accurate economic justifications of new plants and expansion projects as the contribution is illustrated in the case study.

CHAPTER 6 CONLUSION

6.1 Conclusion

The research shows that a RAM and stochastic simulation models are an important part of calculating production efficiency.

This approach also allowed new factors to be considered in the RAM analysis such as ramp up and ramp down rates, upstream and downstream upsets and storage. RAM modelling defines an availability value. This technique identifies the critical equipment and systems that contribute to lost production and defines the frequency and duration of outages. A critical step when developing a RBD with parallel and series equipment configurations that it needs to be validated by facility engineers. No volumetric result is given in the RAM model.

Operations efficiency modelling uses the output data from the RAM model and adds the complexity of reduced throughput and time based impacts as a result of shutdowns, tankage, ramp up and ramp down of equipment under failure conditions.

The two models together define the overall plant availability and production efficiency, given a proposed plant configuration. The objective was to develop RAM and production efficiency models for multiple facilities with its own unique value chains. These models are used to test the integrated impact of reliability on production given different:

- Maintenance philosophies;

- Shutdowns;
- Tankage;
- Plant configurations; and
- Operating philosophies.

They are also used to identify critical equipment and systems that contribute to lost production and define the frequency and duration of outages. This will allow the manufacturing company to maintain a high level of availability at sustained production rates for the proposed facilities. Two models are always built to meet the project objective. These models are developed at equipment level based on PFD and RBD. The RAM model determines the availability of a facility and provides input into the stochastic simulation model to calculate production efficiency.

The production efficiency model is a high level stochastic simulation model of the overall facility and determines the production efficiency of the facility based on the availability of the units, the sizes of the tanks and the operating rules. This unique combination of two modelling techniques is able to meet the challenge of determining the reliability and production efficiency of a total facility.

The models can increase the life cycle value of facilities by optimising the trade-off between capital, RAM and production efficiency. These models have successively been included in this manufacturing company engineering packages. The beauty of these models is that they have been built in a generic way so that they can be used to design new facilities or improve existing facilities. The associated reliability database and signed off assumptions has captured knowledge of SME’s and created a comprehensive set of reliability data that will be of great value for future projects.

The business partner estimated that the use of the models on a specific design improved availability by over 1%. He equated this to a savings of more than 100 million USD. The value-add delivered by these models will increase as they are used on further projects.

This modelling concept has been presented at international RAM and INFORMS conferences and national conference, ORSSA, to good response.

Future research will be to improve on the production efficiency number. A possible solution may be obtained by adding linear programming to the techniques. However, a lot of research still needs to be done to see if this is a viable option.

CHAPTER 7 REFERENCES

The following list of references includes sources used to prepare this research proposal as well as sources for future use.

Adhikary, D. D. et al., 2012. RAM investigation of coal-fired thermal plants: A case study. *International Journal of Industrial Engineering Computations,* Issue 3, pp. 423-434.

Arnic Research Corporation, 1985. *Availability analysis handbook for coal gasification and combustion turbine-based power system..* Palo Alto: Prepared for Electric Power Research Institute.

Ayers, M. L., 2012. *Telecommunications System Reliability Engineering, Theory, and Practice.* 1 ed. New York: John Wiley & Sons.

Banks, J., 1998. *Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice.* s.l.:Wiley and Sons.

Barlow, R. E. & Proschan, F., 1975. *Statistical theory of reliability and life testing: probability models.* New York: Holt, Rinehart and Winston.

Calixto, E., 2016. *Gas and Oil Reliability Engineering: Modelling and Analysis.* 2nd ed. s.l.:Elsevier.

Cassady, C. R. & Kutanoglu, E., 2005. Integrating preventive maintenance planning and production scheduling for a single machine. *IEEE Transactions on Reliability,* 54(2), pp. 304-309.

Denson, W. et al., 1995. *Non electronic Parts Reliability Data.* s.l.:Wiley Online Library.

Goel, H. D., 2004. *Integrating Reliability, Availability and Maintainability (RAM) in Conceptual Process Design: An Optimization Approach,* Delft: DUP Science.

Henry, C. et al., 2014. A stochastic approach for the simulation of collisions between colloidal particles at large time steps. *International Journal of Multiphase Flow,* Issue 61, pp. 94-107.

Hojjati, S. N. & Noudehi, N. R., 2015. The use of Monte Carlo simulation in quantitative risk assessment of IT projects. *International Journal of Advanced Networking & Applications,* 07(01), pp. 2616-2621.

Jackson, Y., Tabbagh, P., Gibson, P. & Seglie, E., 2005. *DoD guide for achieving and assessing Relaibility, Availability, and Maintaiability.* Alexandria, Reliability and Maintainability Symposium.

Kelton, W. D., Sadowski, R. P. & Sturrock, D. T., 2015. *Simulation with Arena.* 6th ed. New York: McGraw-Hill.

Kumar, U. D., Crocker, J., Knezevic, J. & El-Haram, M., 2012. *Reliability, Maintenance and Logistic Support - A Life Cycle Approach.* London: Kluwer Academic Publishers.

Meyer, M., 2004. *Stochastic Modelling in the Petrochemical Industry (Discrete Event Simulation Based).* Potchefstroom: NWU Ferdinand Postma Library.

Meyer, M. et al., 2011. Innovative deciosion support in a petrochemical production environment. *Interfaces,* 41(1), pp. 79-92.

Mobley, K. R., 2014. *Miantenance Engineering Handbook.* 8th ed. s.l.:McGraw-Hill Professional.

National Research Council, 2012. *Assessing the Reliability of Complex Models.* Washington, DC: The National Academies Press.

Nutaro, J. J., Schryver, J. C. & Haire, M. J., 2012. *The throughput, reliability, availability, maintainability (TRAM) methodology for predicting chemical plant production.* Reno, Annual Reliability and Maintainability Symposium.

O'Connor, P. D., Newton, D. & Bromley, R., 2002. *Practical Reliability Engineering.* 4th ed. West Sussex: John Wiley & Sons.

Parthanadee, P. & Buddhakulsomsiri, J., 2014. Production efficiency improvement in batch production system using value stream mapping and simulation: a case study of the roasted and ground coffee industry. *Production Planning & Control,* V(25), pp. 425-446.

Rajpal, P. S., Shishodia, K. S. & Sekhon, G. S., 2006. An artificial neural network for modelling reliability, availability and maintainability of a repairable system. *Reliability Engineering and System Safety,* 91(7), pp. 809-819.

ReliaSoft Corporation, 2016. *BLOCKSIM/RENO 10 User's Guide.* 10th ed. Tucson: ReliaSoft Publishing.

Ritter, S., 2013. Monte Carlo integration – a case-study for simulation. *International Journal of Mathematical Education in Science and Technology,* pp. 131-145.

Saraswat, S. & Yadava, G., 2008. An overview on reliability, availability, maintainability and supportability (RAMS) engineering. *IJQRM,* 25(3), pp. 330-334.

Sutton, I., 2010. *Reliability, Availability and Maintainability, Process Risk and Reliability Management.* Oxford: William Andrew Publishing.

The OREDA Particpants, 2015. *OREDA 2015.* 6 ed. Norway: Published by OREDA participants.

van der Westhuizen, F., 2014. *The effect of combining reliability, availability and maintainability modelling and stochastic simulation modelling on production efficiency.* Parys, ORSSA.

Wang, L., 2012. *Production Assurance and Life Cycle Cost Evaluation of Offshore Development Projects in the Conceptual Design Phase,* Trondheim: Faculty of Engineering Science and Technology Department of Production and Quality Engineering.

Zou, X. & Wang, K., 2014. Numerical simulations and modeling for stochastic biological systems with jumps. *Communication in Nonlinear Science and Numerical Simulation,* Issue 19, pp. 1557-1568.

Appendix A Article 1

The effect of combining Reliability, Availability and Maintainability Modelling and Stochastic Simulation Modelling on Production Efficiency: A Case Study

Philip Pretorius & Jacques van der Westhuizen

ABSTRACT - For multiple years, Petroleum Company's has demonstrated its innovative spirit in the energy and chemicals sectors in South Africa and has grown to become the country's leading fuel provider and an international leader in synthetic fuel production. Ensuring Petroleum Company's success requires that complex operations be managed across value chains, business units, and sites. Nowadays, Petroleum Company's Decision Support Groups apply a wide range of advanced analytics techniques including optimisation, system dynamics, stochastic simulation, and Reliability, Availability, and Maintainability (RAM) modelling. Petroleum Company's worldwide are currently using these modelling techniques to good effect and has built numerous discrete-event simulation models.

Keywords: RAM study, RAM modelling, stochastic modelling, production efficiency, validation

I. INTRODUCTION

Historically, the design phase of a capital project mainly focused on the engineering and design specifications of the equipment, such as process capacity, design duty, heat and mechanical stresses.

Reliability life cycle studies were seldom performed in the past (Adhikary, et al., 2012). Designing for reliability is increasingly becoming mandatory and the results of reliability, availability and maintainability (RAM) modelling studies are critically evaluated in the "gate transition reviews" by the capital project management team.

There are various industry accepted reliability tools and methods for a reliability professional to deploy. Each method has its applications and limitations. A RAM simulation study is ideal for analysing and illustrating the business benefits of each design scenario.

A. Stochastic Simulation

Discrete event simulation, and in this case Arena®, is a tool not traditionally used in continuous environments for design purposes (Kelton, et al., 2015). Most petrochemical companies, use Arena® in a continuous environment during design of modifications to existing facilities and for the identification of infrastructure constraints in fuel blending scenarios. In these areas the value of Arena® is to dynamically evaluate the required changes in the integrated environment.

Interactions between facilities can be considered and the influence of integrated operation on planned throughput can be calculated. The impact of failures and scheduled maintenance in the facility modifications can be estimated and any adjustment to infrastructure or facility capacity can be made before money is invested (Banks, 1998).

B. RAM modelling influencing Stochastic Simulation

There is little research done on this topic. RAM modelling influencing stochastic simulation is currently the status quo of the models executed for capital projects that are currently done by most petroleum companies.

Points to remember when applying RAM modelling to stochastic simulation models (Jackson, et al., 2005):

- The RAM modeller's and stochastic simulation modeller's data needs to be aligned;
- The same time unit measures need to be used in the two models for example; hours, minutes, days etc. Although simulation modelling additionally measures throughput, both models use Mean Time between Failure (MTTF) and Mean Time to Repair (MTTR) data.

RAM modelling calculates the availability of all components in the sub-system. Stochastic simulations have all the sub-systems in its model. Because a stochastic simulation calculates the throughput of the system, RAM modelling and stochastic simulation modelling have the sub-systems in common and that is why the two models overlap with one another (Nutaro, et al., 2012). If one knows what the reliability of a certain component or system is, one will also know what effect there will be on throughput for typical production processes. However, production at a manufacturing company is not typical. It is highly integrated and includes complexities like feedback loops, use of storage facilities, multiple possible destinations for products, variable rates of operation of different units and impact of bottlenecks. By combining stochastic simulation and reliability modelling, the following questions can be answered:

- If a component or system has low or high availability, how does this influence the throughput?
- Which components were the biggest contributors to the downtime experienced?
- Which components were the biggest contributors to the loss of volume throughput experienced?

C. Facility Layout

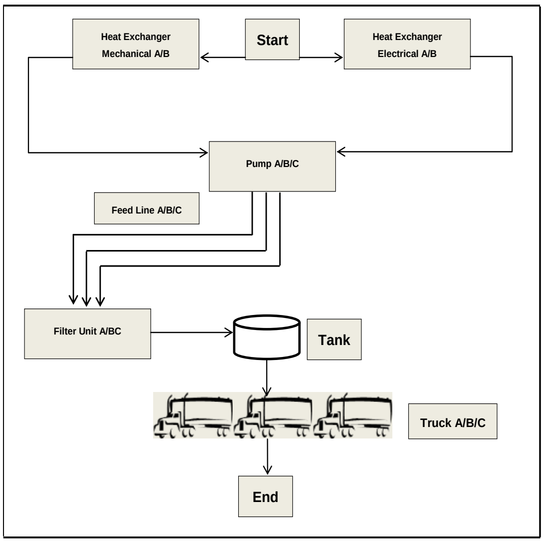


Figure 1 Unit A and tank layout

D. RAM simulation modelling

RAM models are used to define an availability value. This technique identifies the critical equipment or systems that contribute to lost production and define the frequency and duration of outages. The RBD diagram with parallel and series equipment configurations should be the same as the PFD provided by the facility. No volumetric result is included as part of the RAM study.

The model runs in hourly intervals with a simulation length of 35040 hours or 4 years and for 5000 repetitions.

RAM modelling is simulation based modelling used to predict and analyse the life cycle of equipment systems in terms of reliability, availability and maintainability.

RAM modelling takes the following into account:

- The proportion of time a system is in a functioning condition and able to operate;
- Ability of equipment, machine, or systems to consistently perform its intended or required function or mission;
- Includes unplanned failures (i.e. trips and equipment failures); and
- Assumes repair to new.

Initial start-up period of the facility and ramp-up and ramp-down times are excluded from this calculation. Ramp-up and ramp-down are covered in process efficiency calculations.

E. RBD of Facility

The RBD of the proposed facility looks like the Figure below.

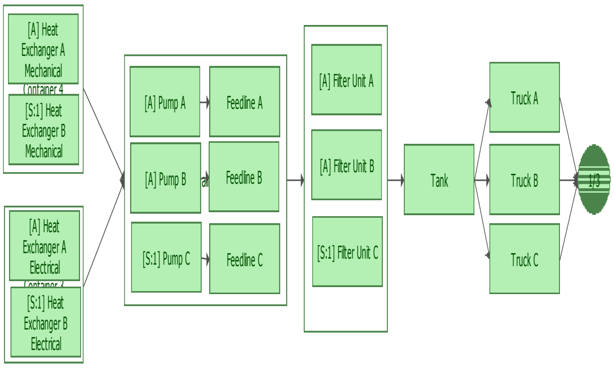


Figure 2 Reliability block flow of facility

The RBD of the facility described in the diagram above. The RBD consists of a complex configuration of series and parallel connections.

i. Equipment data

	MTBF			MTTR		
Equipment	Distribution	Mean (hours)	Years	Distribution	Mean (hours)	Std dev
Feedline A	EXP	1752	0.20	NOR	24	2.4
Feedline B	EXP	1752	0.20	NOR	24	2.4
Feedline C	EXP	1752	0.20	NOR	24	2.4
Filter Unit A	EXP	25.76	0.00	NOR	3.24	0.0967
Filter Unit B	EXP	25.76	0.00	NOR	3.24	0.0967
Filter Unit C	EXP	25.76	0.00	NOR	3.24	0.0967
Heat Exchanger A Electrical	EXP	100000	11.42	NOR	56	5.6
Heat Exchanger A Mechanical	EXP	100000	11.42	NOR	56	5.6
Heat Exchanger B Electrical	EXP	100000	11.42	NOR	56	5.6
Heat Exchanger B Mechanical	EXP	100000	11.42	NOR	56	5.6
Pump A	EXP	8760	1.00	NOR	76	7.6
Pump B	EXP	8760	1.00	NOR	76	7.6
Pump C	EXP	8760	1.00	NOR	76	7.6
Tank	EXP	70080	8.00	NOR	48	4.8
Truck A	EXP	2555	0.29	NOR	72	7.2
Truck B	EXP	2555	0.29	NOR	72	7.2
Truck C	EXP	2555	0.29	NOR	72	7.2

Table 1 Unit A

This methodology makes a constant failure rate assumption. This means that the failure rate is independent of age while functioning.

A mean time to failure (MTTF) and mean time to repair (MTTR) is calculated for each identified failure type. Equipment may have multiple failure types. An assumption has been taken of a standard deviation of 10% from the mean on Normal PDF for MTTR.

ii. Results from the RAM model

The RAM model simulation summary is in the table below

Simulation Summary	
Number of Simulations:	5000
End Time:	35040
Seed Value:	1
System Overview	
General	
Mean Availability (All Events):	0.9988
Std Deviation (Mean Availability):	0.001
Mean Availability (w/o PM & Inspection):	0.9988
Point Availability (All Events) at 35040:	0.999
Reliability(35040):	0
Expected Number of Failures:	18.1468
Std Deviation (Number of Failures):	4.3751
MTTFF:	1991.712
System Uptime/Downtime	
Uptime:	34996.88
CM Downtime:	43.1157
Inspection Downtime:	0
PM Downtime:	0
Total Downtime:	43.1157
System Downing Events	
Number of Failures:	18.1468
Number of CMs:	18.1468
Number of Inspections:	0
Number of PMs:	0
Total Events:	18.1468

Table 21 Simulation summary of RAM model

Overall availability calculates to a percentage of 99.88%. Table 2 shows the biggest contributors as to why the overall facility has an unavailability of 0.12% over a 4-year period. The calculation of the "% Contribution to Downtime" in table 3 works as follows: Each piece of equipment contributes to the total unavailability of 0.12% and in this case, the Filter Unit Section contributes 97.08% of 0.12% unavailability.

The following table is the output file generated from the model.

Equipment	% Contribution to Downtime	Availability	Expected NOF	Block Downtime	Block Uptime
Truck A	0.06%	97%	13	961	34079
Truck B	0.06%	97%	13	958	34082
Tank	2.69%	100%	0	23	35017
Filter Unit Section	97.08%	99%	18	19	35021
Filter Unit A	0.00%	89%	1207	3911	31129
Filter Unit C	0.00%	100%	30	98	34942
Filter Unit B	0.00%	89%	1208	3912	31128
Pump B	0.00%	99%	4	297	34743
Pump C	0.00%	100%	0	0	35040
Pump A	0.00%	99%	4	294	34746
Feedline A	0.00%	99%	19	467	34573
Feedline B	0.00%	99%	20	468	34572
Feedline C	0.00%	100%	0	0	35040
Heat Exchanger A Electrical	0.00%	100%	0	19	35021
Heat Exchanger B Electrical	0.00%	100%	0	0	35040
Heat Exchanger B Mechanical	0.00%	100%	0	0	35040
Heat Exchanger A Mechanical	0.00%	100%	0	19	35021
Truck C	0.06%	97%	13	950	34090

Table 22 Biggest Contributors to Downtime in the Unit A facility.

The Filter Unit Section contributes 97.08% to the unavailability. In essence, the filter unit section with its three filters is responsible for the 97.08% of the unplanned maintenance in the proposed facility.

F. Validation between reality and simulation

The maintenance and reliability department is responsible for storing files containing historical equipment failure data. Equipment failure data is prepared by the RAM modeller and entered into the RAM simulation model. When data is not available from the facility OREDA is used as input.

Table 2 is a simulation summary is given of an output file generated by the software. The expected failure number (FN) should coincide with the data received from the facility. A process flow diagram is given to the RAM modeller and the facility is developed accordingly to the equipment that switches the facility on or off.

The file generated by the facility and generated by the RAM modeller looks as follow:

	Total Failures
Facility data - Actual	43
Simulation output - FN	43.11

Table 23 Equipment failure validation file

It is clear that the output file generated by the facility and the expected FN are the same. Validation between facility and simulation data is crucial. For the number to be exact or statistically correct the configuration in the RAM needs to be correct as well. Once validated, the RAM results are used as input into the stochastic simulation model.

Facility volume data, also known as mass balance data, is used as input into the stochastic simulation model. Mass balance is based on the principle of volume in equals volume out irrespective of quantity produced.

Validation includes the comparison of actual results and simulation results. All operating rules used in the stochastic model, including the operating philosophies, need to be validated. Within the manufacturing environment, the stochastic model is deemed valid if the deviation between actual data and simulation results are within a 5% range. Exceptions do occur in cases where actual data is not available or the deviations can be explained e.g. change of philosophies or demand during the year.

G. Sensitivity Analysis on MTTF Reliability data

When one wants to implement MTTF it has to go through rigorous simulation testing. First, one needs to test the MTTF with different RBD configurations to get the desired results. There are three RBDs that will be used three times each with different MTTFs.

The three RBD configurations are:

a. All four pieces of equipment are in series.

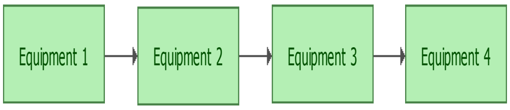


Figure 3 Series configuration

$$R_S = R_{eq1} R_{eq\,2} R_{eq3} R_{eq4} R_{eq\,5}$$

b. Half of the equipment is in parallel and the other half in series.

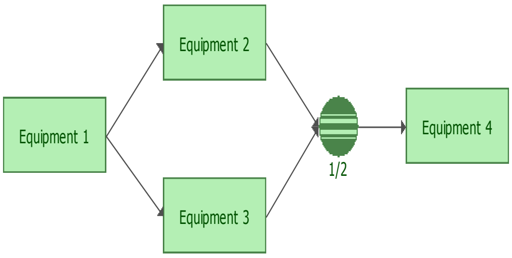


Figure 4 Half parallel and half series configuration

$$R_S = [R_{\frac{1}{2}}\,(1 - \left((1 - R_{eq2})(1 - R_{eq3})\right))]\, R_{eq1} R_{eq4}$$

c. Three pieces of equipment in parallel and one in series.

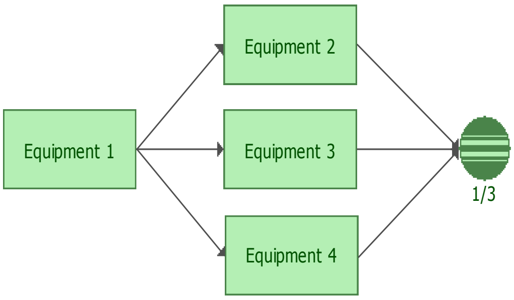


Figure 5 Three pieces of equipment in parallel and one piece of equipment in series configuration

$$R_S = [R_{\frac{1}{3}}\,(1 - \left((1 - R_{eq2})(1 - R_{eq3})(1 - R_{eq4})\right))]\, R_{eq1}$$

Following are nine different scenarios that will be proposed and each of them has a specific outcome. The RBD for each scenario has four pieces of equipment with a specific configuration and different MTTF. For all the scenarios the MTTR was kept at a constant mean of 114 hours and a standard deviation of 11.4 hours. The scenarios are described in table 10. The simulation was run for 8000 years and 5000 simulation runs and the trend line for each diagram will also be added. The reason for a 8000 year simulation run is to see a trend on equipment that would fail once every 200 years. The more simulation runs the more correct your answer. The following equation shows trend line formula that will be used.

$$y = mx + b$$

Table 5 below describes all the scenarios for each configuration.

Scenario	Configuration
1	200 Year MTTF - all 4 pieces of equipment in series
2	200 Year MTTF – 2 pieces of equipment in series, 2 pieces of equipment in parallel
3	200 Year MTTF – 1 piece of equipment in series, 3 piece of equipment parallel
4	50 Year MTTF - all 4 pieces of equipment in series
5	50 Year MTTF - 2 pieces of equipment in series, 2 pieces of equipment in parallel
6	50 Year MTTF - 1 piece of equipment in series, 3 pieces of equipment parallel
7	10 Year MTTF - all 4 pieces of equipment in series
8	10 Year MTTF - 2 pieces of equipment in series, 2 pieces of equipment in parallel
9	10 Year MTTF - 1 piece of equipment in series, 3 pieces of equipment parallel

Table 5 Types of scenario testing MTTF

H. Scenarios

i. Scenario 1

Scenario 1 looks at a 200 year MTTF where all four pieces of equipment are in series.

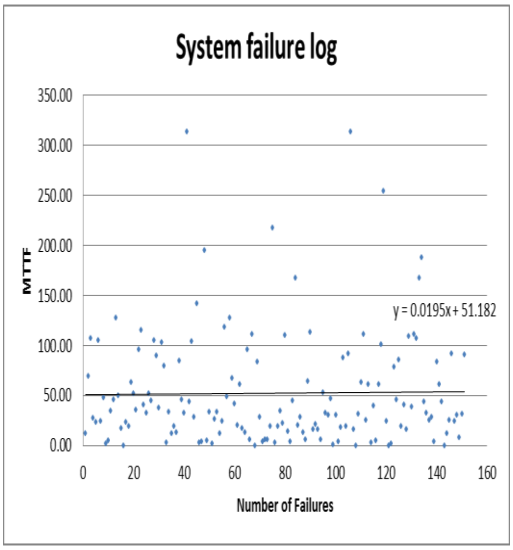


Figure 6 MTTF 200 years – all 4 pieces of equipment in series log

Scenario 1 is where all four pieces of equipment are in series. In other words, each one, when it fails, has an impact on the system. In this specific scenario, each piece of equipment will expect to fail once every 200 years. When running all four pieces of equipment in a simulation model, the model will expect to fail once every 50 years, because each piece of equipment has equal weight sharing. The trend line added to the Figure illustrates that point. The intercept need to be close to 50 years as shown in Figure 6.

ii. Scenario 2

Scenario 2 depicts two pieces of equipment in series and two pieces of equipment in parallel over a 200 year MTTF.

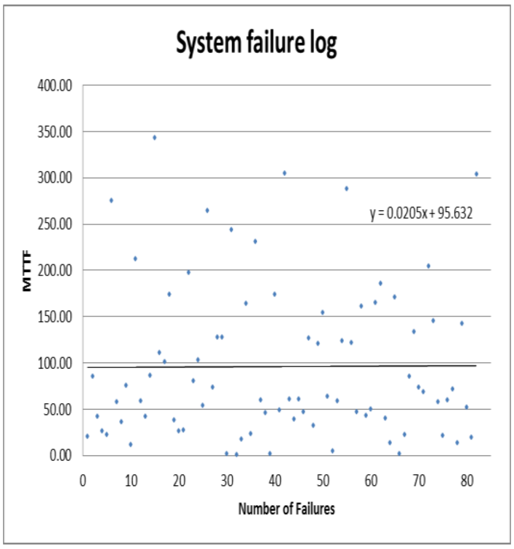


Figure 7 MTTF 200 years – two pieces of equipment in series, two pieces of equipment in parallel

Scenario 2 has two pieces of equipment in series and two in parallel. This would mean that the two pieces of equipment in parallel won't bring down the system and the two pieces of equipment that are in series will bring down the system. One will also have fewer failures because of the configuration. In this case, the trend line shows that the average MTTF is close to 100 years.

iii. Scenario 3

In this Scenario, the configuration is three pieces of equipment in parallel and one in series.

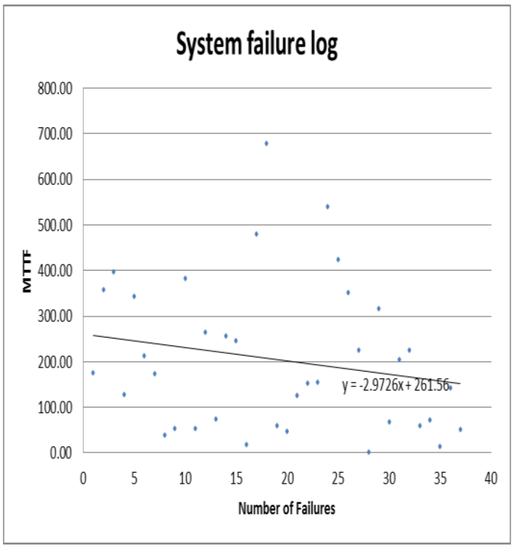


Figure 8 MTTF 200 years – three pieces of equipment in series, one piece of equipment in parallel

In Scenario three only one piece of equipment can fail over a 200 year MTTF. The other three pieces of equipment are in parallel and won't affect system availability. This means that running the model over an 8000 year period with only one piece of equipment that might fail; one would see fewer failures as proven by the trend line added to the Figure.

iv. Scenario 4

Scenario 4 has, like Scenario 1, the same configuration but with one difference. The MTTF for each piece of equipment is 50 years.

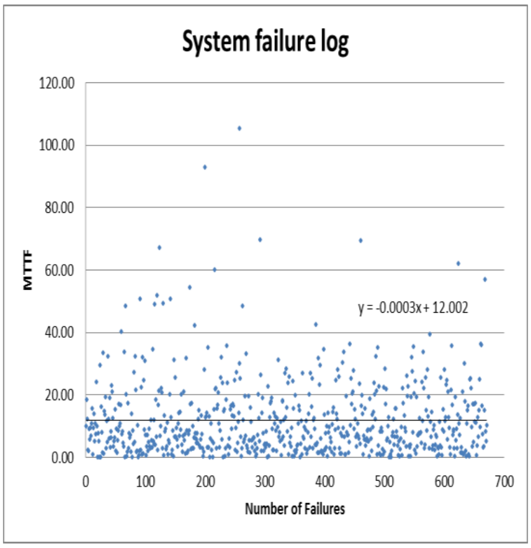


Figure 9 MTTF 50 years – all 4 pieces equipment in series

Scenario 4 will shows there are a lot of failures that happen because all four pieces of equipment has the ability to bring down the system. Over a 50 year period with four pieces of equipment in series, the trend line shows that the average MTTF is close to 12.5 years.

v. Scenario 5

Scenario 5 has two pieces of equipment in series and two pieces of equipment in parallel with each piece of equipment having a MTTF of 50 years.

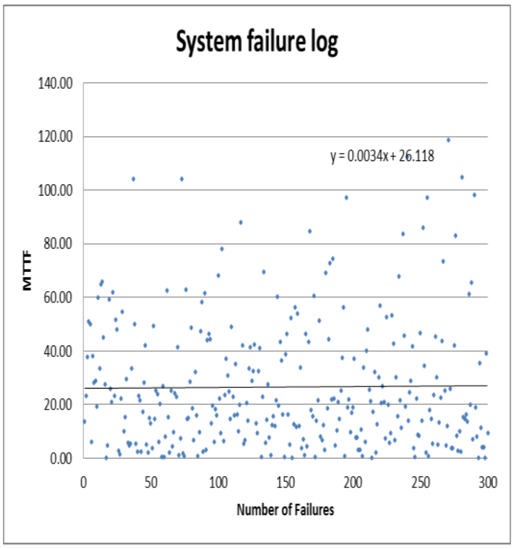


Figure 10 MTTF 50 years – two pieces of equipment in series, two pieces of equipment in parallel

The above scenario will have fewer failures than scenario 4 because only two pieces of equipment can switch off the system. With a MTTF of 50 years for each piece of equipment, the trend line is averaged out at with a MTTF of 25 years.

vi. Scenario 6

Scenario 6 is has three pieces of equipment in parallel and one piece of equipment in series with a MTTF for each piece of equipment at 50 years.

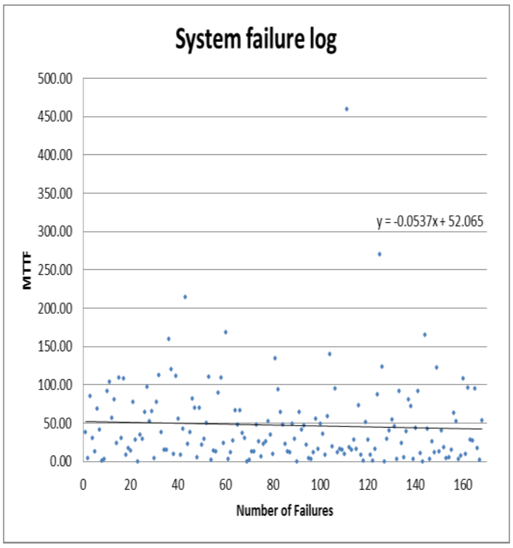


Figure 32 MTTF 50 years – three pieces of equipment in series, one piece of equipment in parallel

In scenario 6 there is only one piece of equipment that could switch the system off. One will have fewer failures because of only one piece of equipment that will have an impact on availability as evident by the trend line stabilising at 50 years. The trend line suggests the intercept is at 52.065 years.

vii. Scenario 7

Scenario 7 has four pieces of equipment in series with each piece of equipment having a MTTF of 10 years.

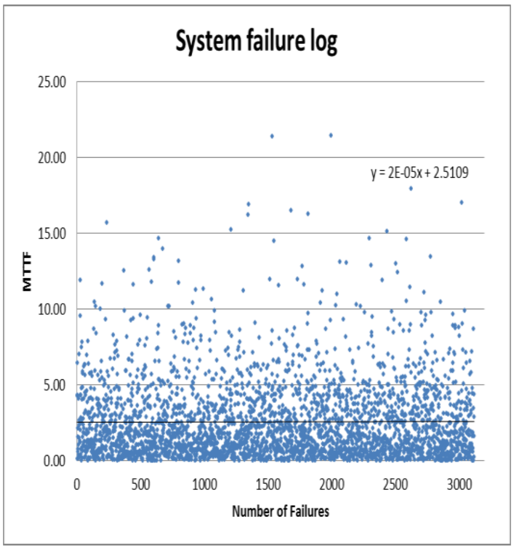


Figure 12 MTTF 10 years – all four pieces of equipment in series

Each piece of equipment has the potential to bring down the system. In this specific scenario, over an 8000 year simulation run, the system will go down every 2.5 years as shown by the trend line. This scenario shows the most failures out of all the scenarios. The more data there is the better fit the trend line will provide. The intercept here is 2.5 years.

viii. Scenario 8

Scenario 8 has two pieces of equipment in series and two pieces of equipment in parallel with a 10 year MTTF for each piece of equipment.

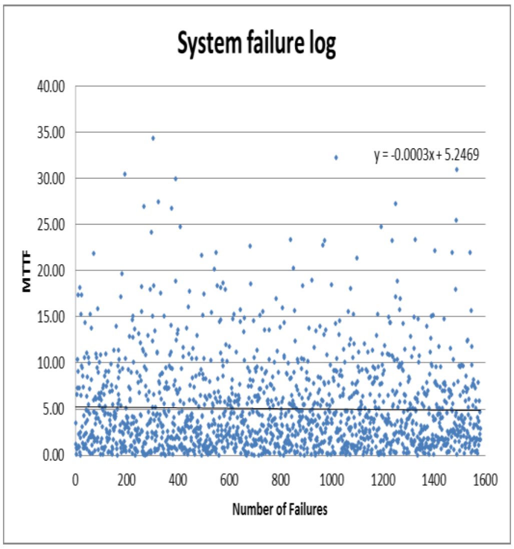


Figure 13 MTTF 10 years – 2 pieces of equipment in series, 2 pieces of equipment in parallel

Scenario 8 has fewer failures than scenario 7, because of its configuration. With a trend line averaging out at 5 years, it is evidently that only two pieces of equipment in series will bring down the system.

ix. Scenario 9

Scenario 9 has three pieces of equipment in parallel and one piece of equipment in series with each piece of equipment having a 10 year MTTF.

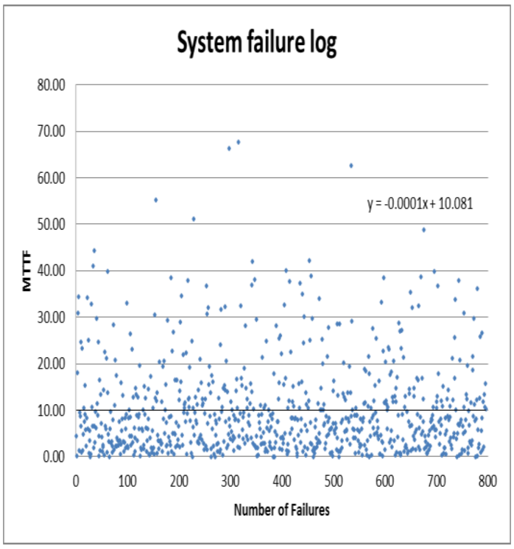


Figure 14 MTTF 10 years – three pieces of equipment in series, one piece of equipment in parallel

Scenario 9 has only one piece of equipment that could bring the system down. Because of the MTTF for each piece of equipment being 10 years and only one piece of equipment in series, one will have fewer failures, but enough for the simulation model to stabilise with a trend line of 10 years.

x. MTTF testing results

The table below gives the output of the MTTF testing results.

Scenarios	Total amount of events	Availability	Unavailability	Equivalent days unavailable	Equivalent hours unavailable
1	151	99.97%	0.03%	0.11	2.63
2	82	99.98%	0.02%	0.07	1.75
3	37	99.99%	0.01%	0.04	0.88
4	671	99.90%	0.10%	0.38	9.11
5	300	99.95%	0.05%	0.19	4.56
6	168	99.97%	0.03%	0.09	2.28
7	3118	99.48%	0.52%	1.89	45.36
8	1551	99.74%	0.26%	0.95	22.75
9	796	99.87%	0.13%	0.47	11.39

Table 6 Types of scenario testing MTTF

When one compares the total failures to the availability, it is clear that all availability is high. Scenario 7, 8 and 9 shows the lowest availability, but also has the highest failure number. The more failures there are, the higher the probability that the model's trend line will be stable as seen in Figure 12, 13 and 14 in the previous section.

Figure 15 shows the total failures vs. availability. The more failures one have the lower the availability will be as depicted below.

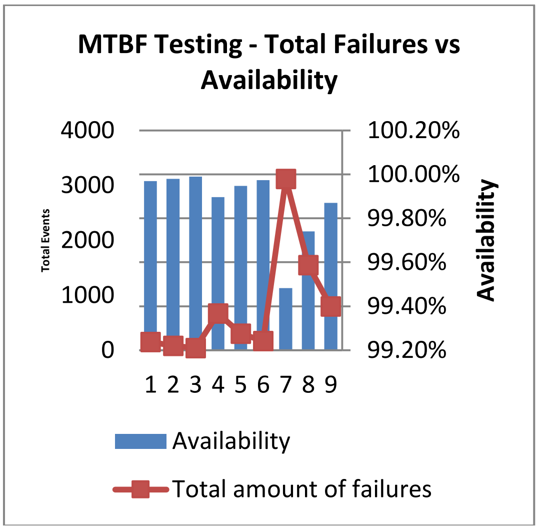


Figure 15 MTTF Testing – Total Failures vs Availability

I. Sensitivity Analysis on MTTR Reliability data

Below are five different cases and each one test the availability with different time points. Each case looks at MTTF at, 025 years, 0.5 years, 1 year, 2 years, 4 years, 6 years, 8 years, 10 years, 15 years, 20 years and 30 years. One piece of equipment was used for this sensitivity analysis experiment. What was proven in this sensitivity analysis is that the smaller the MTTR gets, in essence, the quicker your equipment is repaired and the higher your availability will be. All MTTR's will be modelled with a normal distribution and each MTTF will be modelled with an exponential distribution. The cases are as follow:

Case 1 – MTTR 24 hours

Case 2 – MTTR 12 hours

Case 3 – MTTR 6 hours

Case 4 – MTTR 3 hours

Case 5 – MTTR 0.5 hours

J. Results of MTTR impact on availability

All 5 cases where the MTTR impact on MTTF

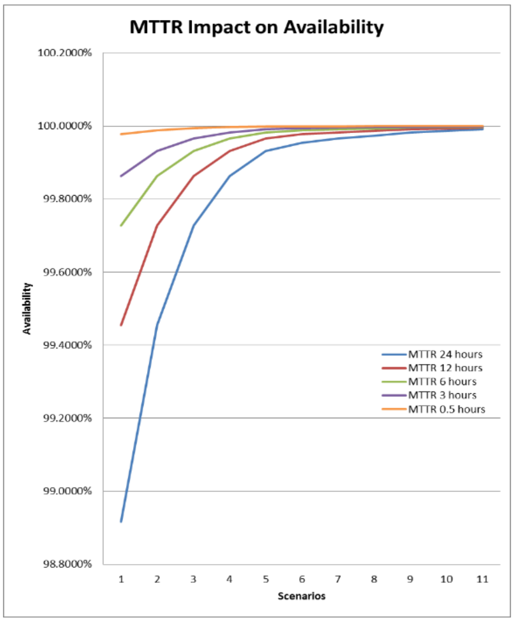


Figure 16 MTTR impact on Availability

Figure 16 shows the impact of all five cases. The MTTF for each scenario stayed the same for every case. The MTTR for every case has changed as well to see the impact of a stabilised MTTR on equipment that would fail at different times.

The results are conclusive in saying that the quicker equipment gets repaired, the higher the availability of a system, and the higher the production efficiency number.

K. Stochastic Simulation and Production Efficiency Results

Production efficiency is determined with a high-level stochastic simulation model and used to predict and analyse the throughput estimate for the facility design.

Arena® is a discrete event simulation modelling tool used to predict the system-wide impact of operating rules and alternatives including reduced capacity during failures or phased shutdowns, ramp-up as well as the impact of buffers. The model runs in hourly intervals with a simulation length of 8 years and for 500 repetitions.

This simulation model uses failures from the results of the RAM model as input.

The production efficiency model considers the following:

- Reduced rates as a result of failures;
- Ramp-up time and shutdown time;
- Impacts of tanks;
- Planned shutdowns; and
- Operating rules (alternative flow during failures):
    - If a unit or sub-system is shut down, can feed be rerouted to an alternate destination?
    - What backup volume is available for downstream facilities?
    - Are there recycle options to keep the unit online?; and
    - What shuts down first and under what conditions?

Initial start-up period of the plant and ramp-up and -down times are excluded from this Unit A study.

A base simulation model was developed. Scenarios were created on this base model where a portion of the model was deactivated or removed. For example, the restart times after a breakdown were removed to indicate the impact of the restart times on the production efficiency. In the first case the restart times after a breakdown were removed as well as the tank constraints in the model and the planned shutdowns and ramp-up times of the units after a planned shutdown. In the next case the restart times after a breakdown are activated. In the following case the tank constraints in the model are activated. In the case thereafter planned shutdowns in the model are activated. With the activation of the restart times after a shutdown in the following case the model has all the deactivated parts on.

The following list shows the order in the cases was run.

- Only breakdowns activated;
- Add the restart times after a breakdown;
- Add the tank constraints in the model;
- Add planned shutdowns;
- Add ramp-up times after a shutdown.

This phased approach was used to show the percentage reduction that each had on the production efficiency. Due to the interactive nature of the facility the cases could be interpreted in isolation. For example, with shutdowns added there are less time available for the units to break down; thus, the units break less than in the breakdowns only scenario. The following table shows the production efficiency of each case and the delta reduction in production efficiency.

Table 12 shows the production efficiency of each scenario and the delta reduction in production efficiency. The maximum average production efficiency that can be achieved under the current assumptions and availabilities is 88.54%.

Scenario	Production Efficiency (%)	Delta reduction (%)
Failures – RAM results	96	4
Add unit restart times	95.5	0.5
Add tanks	95.25	0.25
Add planned shutdowns	89.5	5.75
Add unit ramp up times after shutdown	88.54	0.96

Table 7 The production efficiency of the different scenarios

Note that reduction in table 12 starts from 100%

Figure 17 below shows the production efficiency of each simulation run for the shutdown scenario. This shows the spread of production efficiency values generated by the simulation. The average production efficiency is shown as a red line on the Figure. The 95% production efficiency confidence interval is (88.47, 88.62).

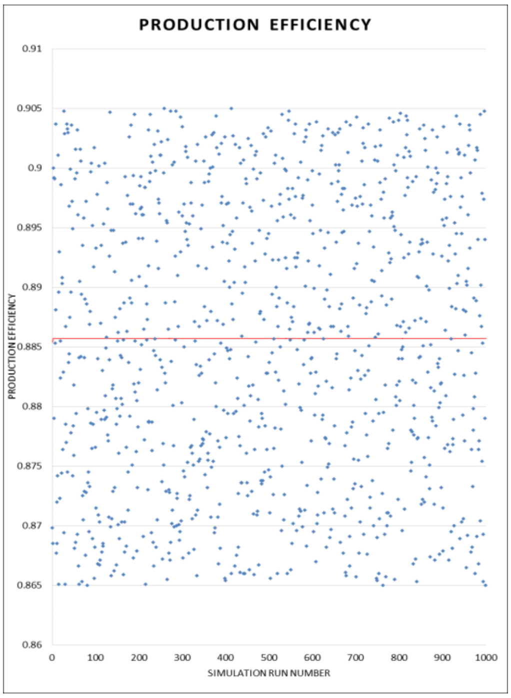


Figure 17 Diagram of the tank average level as a percentage of time

L. Production Efficiency model conclusions

The RAM model determines the availability of the facility and provides input into the production efficiency model. The production efficiency model is a high level stochastic simulation model of the facility and determines the production efficiency of the facility based on the availability of the units, the sizes of the tank and the operating rules.

The average production efficiency of the facility is 88.54% and the shutdowns provide the biggest reduction in production efficiency of 5.75%. The sizes of the tanks are responsible for an average reduction of 0.59% in the production line. The size of the tank is interconnected with other tanks in the facility; increasing the size of one tank will shift the bottleneck to other areas of the facility.

Figure 18 below shows that ramp-up and ramp-down are not calculated in the model. This data tends to skew the answer and only the steady state is taken into consideration.

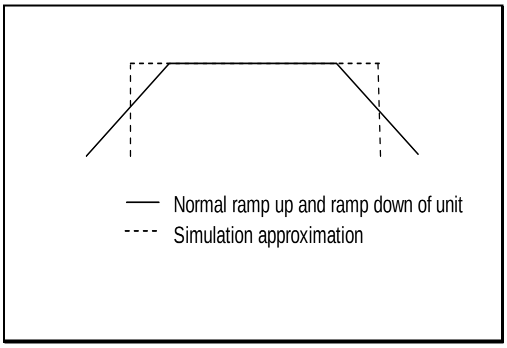


Figure 18 Ramp-up and ramp-down simulation

Table 13 reflects 8 years of planned maintenance or shutdowns built into the model. Every second year the shutdown period in the oil and gas industry changes due to the law. The reason for this is environmental legislation. Legislation states that large equipment needs to be maintained as well. It takes 25 days to do maintenance on these large vessels.

Year after start up	Days shutdown
1	2
2	25
3	2
4	25
5	2
6	25
7	2
8	25

Table 8 Planned shutdown duration in days

II. RESULTS AND DISCUSSIONS

The main purpose when developing a RAM model is to analyse the RAM features which can be used as the foundation for the analysis of the reliability data (Jackson, et al., 2005). Reliability data contains failure and repair data. Together with the RAM model, a stochastic simulation model was developed to see what effect the failure and repair data would have on production efficiency.

A conceptual model was developed and showed how a suitable maintenance strategy could be identified based on RAM analysis. The first step for selection of a better maintenance strategy for each component or sub-system is to find its failure rate based on available data from the maintenance reports, failure observations, daily reports, etc.

The concept of importance measures was developed and some importance measures were defined to manage the efforts to improve availability of the system. The availability of a repairable system can be improved by reducing the failure rate or increasing the repair rate of each component. In other words, one needs to find a way to increase the MTTF and decrease the MTTR of a piece of equipment or a system (Calixto, 2016). When the MTTF increases and the MTTR decrease the production efficiency increases.

The intention of this article is to discover and define how to improve the reliability and availability of a repairable system by using RAM analysis. By doing this, ways to improve production efficiency will become clear. In any project, the main requirements for the operation of large and composite systems are usually specified in terms of cost and availability and of equipment reliability, or equivalently in terms of overall operational time and of overall downtime under cost restriction.

Once the reliability of equipment improves, the throughput of a facility increases and evidently, the production efficiency increases. This theory is proved in the case study provided.

These requirements have then to be taken into consideration when the system design stage is in review in order to decide the suitable reliability and availability of each of its pieces of equipment and systems. A slight improvement in the system's reliability and availability is directly related to extra effort from maintenance personnel (Adhikary, et al., 2012). Therefore, it is very important to grow and breed new techniques for reliability and availability equipment and systems with minimum effort.

The availability and reliability of equipment is a good assessment criterion of a system's performance. Availability and reliability values depend on the system's structure and equipment (Jackson, et al., 2005). These values decrease as the equipment's' age increase, i.e. their allocated times are influenced by their interaction with one another, the applied maintenance philosophies and their environments (National Acadamy of Sciences, 2010).
There are two ways to improve the availability of a repairable system, namely:

- Increase the mean time between failures, or in other words, reduce the failure rate of equipment; and
- Improve the repair rate of the structure, system or components, or, in other words, reduce the mean downtime.

III. Conclusion

The study shows that the reliability, availability and maintainability analysis is very useful for decision making about maintenance and improvement strategy. It is a vital outcome when combining reliability, availability and maintainability analysis with stochastic simulation to see the effect on production efficiency. The study shows that reliability should be an integral part of engineering management for the effective utilisation of production. To improve the reliability of equipment, the most important measures requiring immediate attention are to identify and remove the factors causing problems in all steps of the life cycle, such as planning, design, construction, and maintenance, and to evaluate quantitatively the reliability model based on the failure history data.

The study shows that the effect of appropriate maintenance task selection and performance at an appropriate interval of time is essential for optimal production efficiency. The assembly of a proposed maintenance decision diagram is based on the failure rate of a system, which indicates that appropriate data is essential. The first step for selection of a better maintenance plan for each equipment or sub-system is to find its failure rate based on available data from the maintenance reports, failure observations, daily reports, etc., because the judgment for each type of maintenance strategy depends on the situation of equipment in the bathtub curve.

In an operational context, the operators should observe equipment that fails frequently and are critical to the system, since they are needed for the continuous operation of the system.

REFERENCES

[1] E. Calixto, Gas and Oil Reliability Engineering: Modelling and Analysis, 2nd ed., Elsevier, 2016.

[2] ReliaSoft Corporation, System Analysis Reference: Reliability, Availability & Optimization, 7th ed., Tucson: ReliaSoft Publisher, 2007.

[3] The OREDA Particpants, OREDA 2015, 6 ed., Norway: Published by OREDA participants, 2015.

[4] P. D. O'Connor, D. Newton and R. Bromley, Practical Reliability Engineering, 4th ed., West Sussex: John Wiley & Sons, 2002.

[5] S. Saraswat and G. Yadava, "An overview on reliability, availability, maintainability and supportability (RAMS) engineering," *IJQRM,* vol. 25, no. 3, pp. 330-334, 2008.

[6] K. R. Mobley, Miantenance Engineering Handbook, 8th ed., McGraw-Hill Professional, 2014.

[7] H. D. Goel, “Integrating Reliability, Availability and Maintainability (RAM) in Conceptual Process Design: An Optimization Approach,” DUP Science, Delft, 2004.

[8] D. D. Adhikary, G. K. Bose, S. Chattopadhyay, D. Bose and S. Mitra, “RAM investigation of coal-fired thermal plants: A case study,” *International Journal of Industrial Engineering Computations,* no. 3, pp. 423-434, 2012.

[9] X. Zou and K. Wang, “Numerical simulations and modeling for stochastic biological systems with jumps,” *Communication in Nonlinear Science and Numerical Simulation,* no. 19, pp. 1557-1568, 2014.

[10] C. Henry, J.-P. Minier, M. Mohaupt, C. Profeta, J. Pozorski and A. Tanière, “A stochastic approach for the simulation of collisions between colloidal particles at large time steps,” *International Journal of Multiphase Flow,* no. 61, pp. 94-107, 2014.

[11] P. Parthanadee and J. Buddhakulsomsiri, “Production efficiency improvement in batch production system using value stream mapping and simulation: a case study of the roasted and ground coffee industry,” *Production Planning & Control,* vol. V, no. 25, pp. 425-446, 2014.

[12] S. Ritter, “Monte Carlo integration – a case-study for simulation,” *International Journal of Mathematical Education in Science and Technology,* pp. 131-145, 2013.

[13] S. N. Hojjati and N. R. Noudehi, “The use of Monte Carlo simulation in quantitative risk assessment of IT projects,” *International Journal of Advanced Networking & Applications,* vol. 07, no. 01, pp. 2616-2621, 2015.

[14] National Research Council, Assessing the Reliability of Complex Models, Washington, DC: The National Academies Press, 2012.

[15] J. J. Nutaro, J. C. Schryver and M. J. Haire, “The throughput, reliability, availability, maintainability (TRAM) methodology for predicting chemical plant production,” Reno, 2012.

[16] Y. Jackson, P. Tabbagh, P. Gibson and E. Seglie, “DoD guide for achieving and assessing Relaibility, Availability, and Maintaiability,” Alexandria, 2005.

[17] I. Sutton, Reliability, Availability and Maintainability, Process Risk and Reliability Management, Oxford: William Andrew Publishing, 2010.

[18] J. Banks, Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice, Wiley and Sons, 1998.

[19] W. D. Kelton, R. P. Sadowski and D. T. Sturrock, Simulation with Arena, 6th ed., New York: McGraw-Hill, 2015.

[20] P. S. Rajpal, K. S. Shishodia and G. S. Sekhon, “An artificial neural network for modelling reliability, availability and maintainability of a repairable system,” *Reliability Engineering and System Safety,* vol. 91, no. 7, pp. 809-819, 2006.

[21] M. Meyer, *Stochastic Modelling in the Petrochemical Industry (Discrete Event Simulation Based),* Potchefstroom: NWU Ferdinand Postma Library, 2004.

[22] R. E. Barlow and F. Proschan, Statistical theory of reliability and life testing: probability models, New York: Holt, Rinehart and Winston, 1975.

[23] C. R. Cassady and E. Kutanoglu, “Integrating preventive maintenance planning and production scheduling for a single machine,” *IEEE Transactions on Reliability,* vol. 54, no. 2, pp. 304-309, 2005.

[24] W. Denson, G. Chandler, W. Crowell, A. Clark and P. Jaworski, Non electronic Parts Reliability Data, Wiley Online Library, 1995.

[25] Arnic Research Corporation, Availability analysis handbook for coal gasification and combustion turbine-based power system., Palo Alto: Prepared for Electric Power Research Institute, 1985.

[26] L. Wang, “Production Assurance and Life Cycle Cost Evaluation of Offshore Development Projects in the Conceptual Design Phase,” Faculty of Engineering Science and Technology Department of Production and Quality Engineering, Trondheim, 2012.

Appendix B Article 2

Reliability, Availability and Maintainability Modelling and Stochastic Modelling Validation

Philip Pretorius & Jacques van der Westhuizen

***Abstract* - Petroleum companies are currently designing future facilities at various global locations. A Reliability, Availability and Maintainability (RAM) study is an important part of the basic engineering package. State-of-the-art RAM modelling, however, was not able to address the combined variability and complexity of a manufacturing company's facilities. An opportunity thus arose to use stochastic simulation in combination with RAM models to meet the challenge of determining the reliability and production efficiency of a facility. This approach also allowed new factors to be considered in the RAM analysis such as ramp-up/down rates, upstream and downstream upsets and storage. Validation into these models, regardless of it being reliability Figures or production rates, it must be scrutinized.**

Keywords: RAM study, RAM modelling, stochastic modelling, production efficiency, validation

I. INTRODUCTION

Petroleum companies has demonstrated its innovative spirit in the energy and chemicals sectors in South Africa and has grown to become the country's leading fuel provider and an international leader in synthetic fuel production. Ensuring a manufacturing company's success requires that complex operations be managed across value chains, business units, and sites. Technology groups apply a wide range of advanced analytics techniques including optimisation, system dynamics, stochastic simulation, and Reliability, Availability, and Maintainability (RAM) modelling. A world leading manufacturing company is currently using these modelling techniques to good effect and has built numerous discrete-event simulation models.

Major projects containing petroleum companies' unique value chain contributes to its vision and future growth. Further, RAM modelling of key units in the production process, using Monte Carlo simulation, helps to minimise downtime of existing facilities and supports decision-making on new facilities. Combining these two simulation techniques has provided an innovative way to support decisions. The value of these models has been repeatedly shown through improvements to the bottom line for many business units and sites. The two simulation techniques are RAM modelling and stochastic modelling and RAM modelling stochastic modelling; and RAM modelling.

In essence, RAM modelling will be the input for stochastic modelling. Production efficiency can be effectively calculated by a combination of RAM modelling and stochastic modelling.

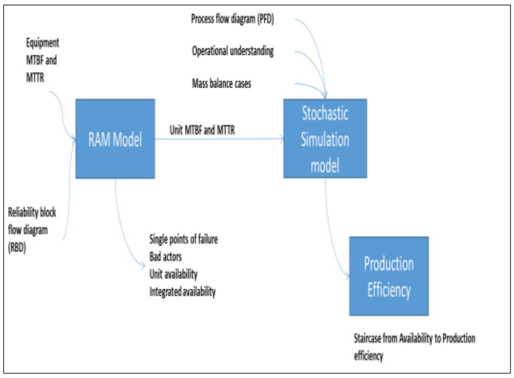


Figure 1: The effect of RAM modelling and Stochastic Simulation modelling on Production Efficiency

A. *Stochastic modelling*

The definition for stochastic modelling is as follows: "A broad collection of methods and applications to mimic the behaviour of real systems, usually on a computer with appropriate software. In discrete-event simulation (DES), the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system" (Banks, 1998). According to Kelton et al. (2005:12) "Arena® combines the ease of use found in high level simulators with the flexibility of simulation languages, and even all the way down to general-purpose procedural languages like the Microsoft®, Visual Basic® or C®. It does this by providing alternative and interchangeable templates of graphical simulation modelling-and-analysis modules that you can combine to build a fairly wide variety of simulation models".

Arena® supports both continuous and discrete processes in a system and consequently also poses the competence to estimate continuous processes in a discrete way (Meyer, 2004). Arena® is hierarchical and the actual model looks much like a flow diagram with different parts of the model being modelled as sub models if required. Arena® also has many animation features to show the progress of entities through the system (Kelton, et al., 2015).

An entity can be a part or a person or whatever needs to move in or through the system. Entities can also be essential, for example where an entity is used to change a variable in the system at specific points in time (Henry, et al., 2014). Meyer (2004:11) states that the value of a variable in Arena® is global and similar to other programming software, and can be seen throughout the model. The characteristic of an entity belongs only to that entity and will be part of that entity as it progresses through the model

B. *RAM modelling*

Like all other industrial regulations, reliability engineering uses highly focused terms with precise meanings. However, many of these terms have different meanings to what is used elsewhere on a day-to-day basis; therefore, the description of terms used in the RAM field is of significance (Adhikary, et al., 2012).

i. Reliability

“The reliability of a component or of a system is the probability that it will perform a required function without failure under stated conditions for a stated period of time. (Calixto, 2016)*”*

Reliability is a fast growing discipline which aims to develop methods and tools to predict, evaluate and demonstrate better input into RAM models. The reliability of any system and component has become a crucial part in the design phase of any company. In the current environment of today’s competitive global economy, companies are forcing manufacturers to produce exceedingly reliable, safe and easily maintainable engineering products.

The above definition integrates the following concepts (O'Connor, et al., 2002):

- Reliability can either refer to the equipment in a system or to the sub-system itself. The current expression of availability has more to do with system analysis;
- Reliability has a likelihood value associated with it; nothing is either certain to function or certain to fail;
- The term required function also features in the above definition. All the equipment and systems are designed for a specific task or sets of tasks. If a piece of equipment is called on to achieve a result on a non-specified task and then fails, the piece of equipment itself was not unreliable;
- In the same way, the stated conditions must be looked at very carefully. For example, if a piece of equipment is not operated in the design temperature range then failure of that piece of equipment does not mean that it was unreliable; and
- By definition, reliability covers only a certain entity of existence. Nothing is built to last forever; ultimately, everything has an end date. The number of simulation cycles could also refer to the beginning and the end of a system, sub-system, or piece of equipment.

ii. Availability

The definition is as follows: *“The availability of a repairable system is the fraction of time that it is able to perform a required function under stated conditions.* (Barlow & Proschan, 1975)*”*

The norm is that availability applies to systems and reliability to equipment within those systems. Reliability and availability are illustrated in the Figure below and the differences are clearly seen. Over time, the value of availability averages out at a high percentage value (O'Connor, et al., 2002). For example, the availability of a facility may be at 95%; this means that the facility is running at 95% of the time the organisation wants it to run. The reliability values for individual pieces of equipment tend to approach ever nearer, but never cross zero. If a piece of equipment is in service for a very long time, and if it is not either repaired or replaced, it will ultimately fail (Goel, 2004). The difference between reliability, availability and maintainability is described in the Figure 2 below:

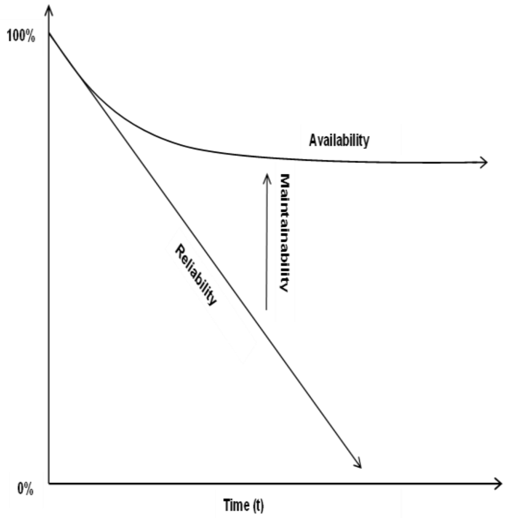


Figure 2: Difference between reliability, availability and maintainability

Define:

R(t) = Reliability;
A(t) = Availability; and
M(t) = Maintainability.

Availability is defined as shown in equation (1.1).

$$A(t) = \frac{MTTF}{(MTTF + MTTR)} \qquad (1.1)$$

In principle, availability is reliability plus maintainability as shown in equation (1.2).

$$A(t) = R(t) + M(t) \qquad (1.2)$$

For example, a system has 365 days between failures and has corrective maintenance done on it for 21 days. The assumption is made that the system would be repaired to new. As it would be repaired to new the system would fail less in comparison to a system that is repaired to old. When a system is repaired to old it means that the current system is not repaired but only fixed and the availability number would decrease over time if this trend continues (Saraswat & Yadava, 2008). Whereas repaired to new mean that when a system has failed it was replaced with a new system. Hence the system availability is:

$$A(t) = \frac{365}{(365 + 21)}$$

$$A(t) = 94.56\%$$

The following example illustrates that it is imperative to take note of repair times when intending to increase availability albeit it is only a fraction of the overall operational time.

A system functions for 17520 hours and at a certain point fails. The repair time is 160 hours. Therefore, the availability of the function is (17520 / 17680), or 99.05%. To increase the availability to 99.50% (which is what management wants) a decision needs to be made on maintainability. This would in essence affect the whole facility. There are two ways to increase availability (Jackson, et al., 2005):

- Option one is to increase the overall run times to 25,000 hours while maintaining the same 160 hour lost time for repairs; and
- Option two is to decrease the time to repair from 160 hours to 90 hours.

The two options mentioned both generate 99.50% availability. One should be very careful in reducing the repair times; the model should reflect what is seen in the facility, in other words, reality.

iii. Production efficiency

If a facility is capable of exceeding market demand by producing more products, the term production efficiency is used instead of availability. Production efficiency is (Nutaro, et al., 2012).

"Production Efficiency is defined by the fraction of total production that could be made at any one time" (Sutton, 2010). When a facility operates day and night and is only producing 50% of the desired output due to uncontrollable factors such as reduced product sales, then its availability is 100%, but its fractional capacity is 50%, so its production efficiency is only 50%. Table 1 shows the example of how production efficiency is calculated.

A facility has an agreed capacity of 500 tons per day. Market capacity shows the amount of material that could be sold. Days 1 and 2 are easy to understand. The facility is available 100% of the time and can sell everything it makes. Thus, it produces the full 500 tons per day. Its production efficiency is 100%. On day 3, the availability falls to 75%, so the production efficiency falls to 75%. On day 7, the facility can only sell 50% of its potential production even though it is 100% available. This means its effectiveness is 50%. On day 12, both the availability and market capacity are 50 %. Thus, the production efficiency is 50% (Sutton, 2010).

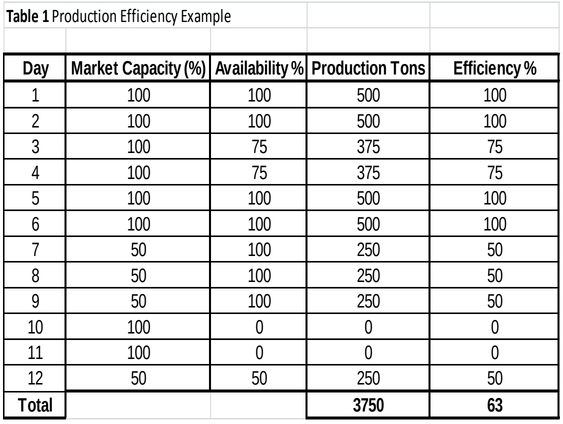


Table 1 Production Efficiency Example

Day	Market Capacity (%)	Availability %	Production Tons	Efficiency %
1	100	100	500	100
2	100	100	500	100
3	100	75	375	75
4	100	75	375	75
5	100	100	500	100
6	100	100	500	100
7	50	100	250	50
8	50	100	250	50
9	50	100	250	50
10	100	0	0	0
11	100	0	0	0
12	50	50	250	50
Total			**3750**	**63**

Table 1 Production Efficiency Example

iv. Maintainability

"The maintainability of a failed component or system is the probability that it is returned to its operable condition in a stated period of time under stated conditions and using prescribed procedures and resources."

Most RAM analyses presume that when a piece of equipment is repaired, it is returned to working condition ''as good as new'' (Adhikary, et al., 2012). The fact is that this assumption is seldom true; most equipment is restored to a condition that is between ''as good as new'' and ''as good as old''. (Mobley, 2014) affirms that "it is in worse condition than when it was brand new, but in better condition than at the time of failure.

II. RELIABILITY, AVAILABILITY AND MAINTENANCE MODELLING

A. *Quantitative Reliability Analysis*

"Reliability is the probability that a piece of equipment, product, or service will be successful for a specific amount of time (Calixto, 2016)."

When one needs to explain the reliability of a piece of equipment, product, it is essential to gather historical reliability data, and in this case, failure data. Consequently, step one in the life cycle analysis is to comprehend how failures happen over time and to explain MTTF and MTTR to see if equipment is achieving the designed reliability (Wang, 2012).

Reliability focuses on the ability of a piece of equipment to perform its intended function when one assumes that a piece of equipment is performing its planned function at time equals zero. The definition of reliability can be described as: “The ability of a piece of equipment to consistently perform its intended or required function or mission, on demand and without degradation or failure. Therefore, the effects of planned maintenance and unplanned maintenance i.e. trips and equipment failures are included (Adhikary, et al., 2012).”

RAM models to a great extent focuses on the data that will be entered into the model. Reliability data to be entered into the model are MTTF and MTTR. MTTF describes the predicted time between two failures that are recurring and MTTR describes the predicted time to repair a piece of equipment that has failed (Nutaro, et al., 2012).

To manage life cycle analysis about equipment, it is essential to have historical data about all the failure modes that took place. “The failure mode is the manner in which a piece of equipment or product loses part or total capacity to perform its function (Kumar, et al., 2012).” Numerous companies in the petrochemical industry do not have historical data for the equipment in the facility, and most of the equipment providers have no reliability data for the products they sell. “Thus, the first step in reliability requests is to gather data, but in most circumstances the modeller who needs the data for life cycle analysis is not the same person who repairs or performs maintenance on the equipment and gathers the data. The crux is that there are few companies that have reliability data and a good deal of companies that don’t (Calixto, 2016).”

It must always be in the back of a manager’s mind of the importance of gathering reliability data for equipment. “Furthermore, employees must be proficient in gathering data and making decisions based on dependable data. This is a big challenge for most companies, because even when procedures and programs are established, it is necessary to collect, assess, and store failure data in files and reports for future access (National Research Council, 2012).”

In the case of reliability data, also known as failure and repair data, has not been recorded, such data can originate in numerous bases such as:

- The Offshore Reliability Data (OREDA) handbook (OREDA, 2015);
- Non electronic Parts Reliability Data (Denson, et al., 1995);
- “Availability Analysis Handbook for Coal Gasification and Combustion Turbine based Power Systems (Arnic Research Corporation, 1985).”

Various reliability modellers see past reliability data as an index, which comprises of the following:

- Constant failure rate;
- Reliability;
- Availability;
- MTTF; and
- MTTR.

The Reliability and Maintainability (RM) data for similar equipment may vary considerably in altered sources (Mobley, 2014). The reason for this is because the data is dependent on operating situations, the observation size, and period. In this case, period refer to duration. Proper data sources lay the groundwork for the quality of concluding results. Nonetheless, there will always be inequality in the data sets (Rajpal, et al., 2006).

The OREDA handbook is the best used data source in the petrochemical industry. It collects data for a large diversity of equipment and systems used in offshore and inland projects. Numerous editions of the OREDA handbook have been issued of which the 6th edition in 2015 is the latest. A computerised database is exclusively available to oil and gas OREDA members (OREDA, 2015).

When RAM analysis takes place, OREDA has the reliability data categorised in failure rate and active repair time. Regarding maintenance data, OREDA caters for both calendar time and operation time. During a RAM analysis, the operational time-dependent data is used. For data that needs to be entered into BlockSim®, the failure rate needs to be converted to MTTF (ReliaSoft Corporation, 2016).

The constant failure rate, which is a function of time, is notably illustrated by the bathtub curve shown in Figure 3:

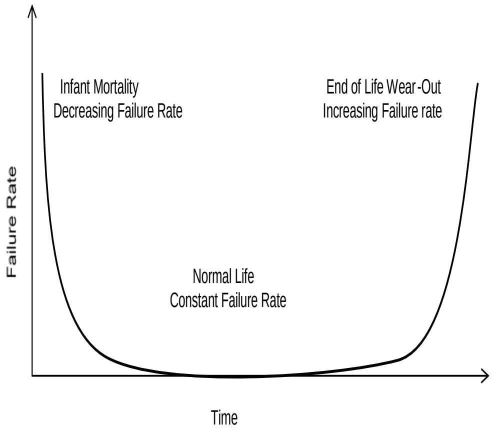


Figure 3: The bathtub curve

When it comes to RAM analysis, it is a widely accepted assumption that the failure rate is constant. This suggests that all ramp up and ramp down failures are ignored. Thus, the constant failure rate implies that the reliability of equipment is measured when it is in a steady state. A life cycle is restricted to the valuable lifetime of the project (Wang, 2012).

In saying this, the MTTF is modelled as an exponential distribution in BlockSim® and Arena®.

"To do a life cycle analysis, the following resulting data, classified by configuration, is required (Calixto, 2016):

- Individual or grouped data;
- Complete data; and
- Interval data."

A piece of equipment is known as individual data. Grouped historical data comes from multiple pieces of similar equipment. It is very important to evaluate equipment for the life cycle calculation. Past failure data from one piece of equipment need to be tested to see if it is adequate. However, for typical equipment like the one mentioned, there must be a great quantity of data to ensure a reliable life cycle analysis (ReliaSoft Corporation, 2016).

There are many cases lacking sufficient historical data. Such historical data is of utmost importance when viewing a comparable piece of equipment with a similar working function and in workable condition to generate a database. In a working environment it can be a challenge finding similar equipment. In several circumstances maintenance, working, and process situations have an effect on the equipment life cycle. "When reliability analysis is led in the pre-feasibility stage, similarity is easier to obtain because operational conditions, processes, and maintenance procedures are similar to project requirements (Calixto, 2016)." However, when one wants to increase the reliability of the life cycle analysis, one should use data that has been historically grouped., In this case it requires considering various equipment that are more or less the same than the equipment in the facility to create Probability Density Functions (PDFs) for the equipment evaluated. In addition it is a necessity to validate equipment likenesses, and in projects this is also easier (Goel, 2004).

When historical data is recorded, the data will be known as complete; in this case one needs to establish a time occurrence, preferably in hours. It is very important to know when the operation started as this will be called the beginning of the life cycle of the equipment. The captured maintenance and operational data will assist in validating when the equipment was online (Adhikary, et al., 2012). In some cases where equipment has no failure data, OREDA will be used as a guideline or as input (Calixto, 2016).

Various types of reports might be used upon failure. However, it is easier for all facility personnel, and those working with data, to understand what type of failure occurred, why it occurred, and to assess if the recommendations conducted solved the type of failure, when looking at the defined failure modes. When defining failure modes, all employees should know what type of failure occurred as they are the ones that will capture the failure. Not knowing the type of failure might lead to incorrect capture.

In some cases the equipment used to create PFDs does not fail in the time being observed. "This is called right censured data and must be included in the analysis for consideration. In the current observed environment, this data is often not taken into account (Cassady & Kutanoglu, 2005)."

When equipment has failed after the original failure was captured, such information does not get logged. This data is very important, however, and should be included in the model the next time a report is due. It might seem like the equipment had high reliability, but in reality there were unreported failures at the beginning of the equipment life cycle influencing reliability (Jackson, et al., 2005).

Another intervention on historical data configuration is done when there's no precise data on equipment failure. In such a case one can do research on the same types of equipment, capturing data showing equipment failure in more or less the same circumstances as the equipment in the current operation.

It is challenging when no data is available. In such circumstances a subject matter expert (SME) may be consulted. Such experts have years' of experience and a wealth of knowledge about the concerned equipment. This information may also be captured in the database.

There are techniques one can use to an advantage to estimate the variable values from the SME opinion (Wang, 2012):

- Aggregated individual method: This method is where SMEs do not meet but make approximations. These approximations are then collected statistically by taking the recognised mean of all the individual approximations.
- Delphi method: In this method, SMEs make their assessments individually and then all the assessments are compiled and showed to the wider group to define.
- Nominal group technique: The nominal group technique is very much the same as the Delphi method, each SME creates an assessment with its own personal style attached to it. These assessments will be combined in a statistically manner.
- Consensus group method: Individually, each member will contribute to the dialogue and as a group they make a final decision on what the final value will be.
- Bayesian inference methodology: This method is a mathematical approach applied to estimation of data based on knowledge gained from previous experience.

The assumed state "as good as new" suggests that the maintenance events repaired the equipment to an "as good as new" state. When one looks at the assumption "as good as old" it means that a piece of equipment was repaired to a state just before it failed and that the piece of equipment expect to fail much quicker than if it was “as good as new” (Mobley, 2014).

B. *Modelling and simulation*

To describe system and sub system availability, equipment PDF parameters need to be defined as input into a system, “a Reliability Block Flow Diagram (RBD) must first be defined and then simulated. To describe a system RBD it is necessary to demarcate the system’s limits prior to execution of the analysis. (Sutton, 2010)” Most of the time an evaluation of sub-systems, equipment, and components are available. Failures of these sub-systems, equipment, and components effect production loss. When one creates a RBD it is important to define a logic effect for any equipment in the system. Thus, the modeller will need to know if the failure of certain equipment means it is switching the system on or not (Wang, 2012).

“If a piece of equipment fails and causes system downtime, a system like that is modelled in series. Though, if two or more pieces of equipment fail and doesn’t switch off the system that type of equipment is modelled in a parallel block, and the whole parallel block is in series with the other blocks.

Thus, it is necessary to set up model equipment using block diagram procedures and be familiar with the mass balance details influencing losses in productivity (ReliaSoft Corporation, 2016).”

To get the availability results after modelling the system in a RBD format it is important to use a recognised approach for example Monte Carlo simulation (Hojjati & Noudehi, 2015). When simulating a whole system, each block that representing one specific piece of equipment will have its own reliability data.

“Thus, Monte Carlo simulation will continue with failures over simulation time for all block PDFs which consists of reliability data. While doing this, if a block fails and it is in series in the RBD, the unavailability will be counted in the system for failure and repair duration over simulation time. Simulation time hinge on how long the system functions based on time recognised (Calixto, 2016).”

i. Monte Carlo Simulation

“The basis of a Monte Carlo simulation is the generation of random numbers. A random number generator is a computational algorithm that generates repeated random numbers (Ritter, 2013).”

Monte Carlo simulation calculates the mean of the output distribution by calculating all of the random generated numbers and dividing it by the number of samples.

The Monte Carlo simulation technique simulates the available uncertainty in the modelling output. This uncertainty is triggered by changing the input variables coming into existence because of different factors; in this case it is the failures and the repair times. When repeating simulation cycles with a large number of times, the results are closer to reality (Hojjati & Noudehi, 2015).

C. *Model validation and prediction*

A quantitative viewpoint states that validation is the process of measuring if the quantity of interest (QOI) for an existing system is within an approximated endurance, this is based on the planned use of the model prediction. However, most of the time prediction occasionally refers to circumstances where no data is available, in this case, reference is made to the output of the model (National Research Council, 2012).

“Validation can be accomplished by directly comparing model outputs to facility output for the QOI and computing a confidence interval for the difference, or carrying out a hypothesis test of whether or not the difference is greater than the tolerance (National Acadamy of Sciences, 2010).” In further settings, a more complicated statistical modelling formulation requires a combined simulation output with different kinds of physical observations, as well as SMEs to create a prediction with add-on prediction uncertainty, which can formerly be used for the assessment (Wang, 2012).

Evaluating prediction uncertainty is vital for both validation and prediction of non-measured QOIs. This doubt characteristically originates from several sources, comprising the following:

- Absence of knowledge about input in the model;
- The difference between model and reality;
- Limited evaluations; and
- Programming errors.

“In typical cases, the verification effort can successfully eradicate the uncertainty due to solution and coding errors, with only the first three sources of uncertainty remaining. Similarly, when the simulation model runs quick, one can evaluate the model at any required input setting, rejecting the need to evaluate what the model would have produced at an untested input setting. (Ritter, 2013)”

The validation and prediction protocol during a basic process includes (Wang, 2012):

- Recognising major vagueness;
- Identifying observations;
- Tests;
- Evaluating prediction uncertainty;
- Evaluating the quality of the prediction;
- Providing evidence on how enhance an valuation; and
- Interactive sessions.

“Identifying and indicating uncertainties generally involves a sensitivity analysis to determine which inputs of the model affect key model outputs. When the uncertainties are identified, one must determine how best to represent these important contributors to uncertainty (Calixto, 2016)."

"The available physical observations are fundamental to any validation assessment. In some cases such data is observational, provided by nature e.g., atmospheric measurements and supernova lights. In other cases, data come from a carefully planned hierarchy of controlled experiments. In adding to physical observations, data may come from the literature or SME's integrating historical data or known physical behaviour (Wang, 2012)."

Estimating prediction uncertainty requires the combination of calculated models, physical observations, and other information sources. How this estimation is supported can range from very straight forward, as in the weather forecasting to quite complicated systems. In these examples, some physical observations are used to refine or constrain uncertainties that contribute to prediction uncertainty.

"For any prediction, evaluating the quality or reliability of the prediction is vital. The concept of prediction reliability is more qualitative more than anything else. Prediction reliability includes (Adhikary, et al., 2012):

- Verifying the assumptions or operating rules on which an estimate is based;
- Examining the available of physical measurements;
- The features of the computational model; and
- Applying a skilled verdict."

"In different validation applications, opportunities exist to do extra experiments to expand the prediction uncertainty and the reliability of the prediction. Estimating how different forms of extra information will improve predictions or the validation assessment is an important component of the validation effort. This can help with decisions about where to invest resources, how long one should do corrective maintenance and how much spare equipment one should keep in order to maximise the reduction of uncertainty and an increase in reliability (Cassady & Kutanoglu, 2005)."

Communicating the results of the prediction analysis is done using both quantitative and qualitative aspects. "While the communication component is not essentially calculated, effective communication may depend on mathematical characteristics of the assessment.

The numerous tasks stated in the previous paragraphs give a comprehensive outline of validation and prediction. Precisely how these tasks are supported depends on the features of the specific application. The list below covers a multiple considerations that will have an effect on the methods and approaches for carrying out validation and prediction (National Research Council, 2012):

- The total amount of relevant physical observations for the assessment;
- The correctness and uncertainty escorting the physical observations;
- The difficulty of the physical system being modelled;
- The computing infrastructure and run time demands of the model;
- The correctness of the computational model's solution comparative to that of the numerical error;
- The correctness of the computational model's solution relative to that of the true model discrepancy;
- The presence of model parameters that need calibration using the available physical observations, and
- The availability of alternative computational models to assess the impact of different modelling techniques."

III. Validation

The following diagram depicts the validation between reality and simulation.

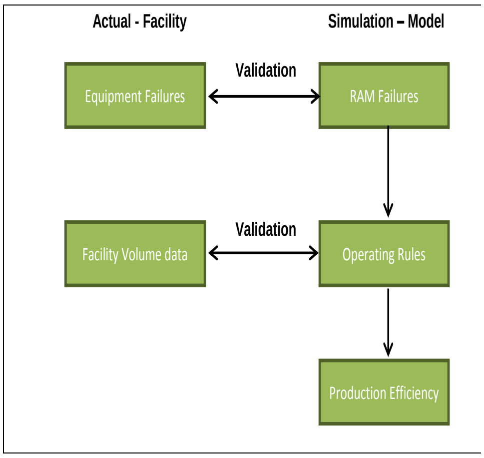


Figure 4 Validation between simulation and actual

A. Validation between reality and simulation

The maintenance and reliability department is responsible for storing files containing historical equipment failure data. Equipment failure data is prepared by the RAM modeller and entered into the RAM simulation model. When data is not available from the facility OREDA is used as input.

In simulation summary is given of an output file generated by the software. The expected failure number (FN) should coincide with the data received from the facility. A process flow diagram is given to the RAM modeller and the facility is developed accordingly to the equipment that switches the facility on or off.

The file generated by the facility and generated by the RAM modeller looks as follow:

	Total Failures
Facility data - Actual	43
Simulation output - FN	43.11

Table 2 Equipment failure validation file

It is clear that the output file generated by the facility and the expected FN are the same. Validation between facility and simulation data is crucial. For the number to be exact or statistically correct the configuration in the RAM needs to be correct as well. Once validated, the RAM results are used as input into the stochastic simulation model.

Facility volume data, also known as mass balance data, is used as input into the stochastic simulation model. Mass balance is based on the principle of volume in equals volume out irrespective of quantity produced.

Validation includes the comparison of actual results and simulation results. All operating rules used in the stochastic model, including the operating philosophies, need to be validated. Within the manufacturing environment, the stochastic model is deemed valid if the deviation between actual data and simulation results are within a 5% range. Exceptions do occur in cases where actual data is not available or the deviations can be explained e.g. change of philosophies or demand during the year.

REFERENCES

[1] E. Calixto, Gas and Oil Reliability Engineering: Modelling and Analysis, 2nd ed., Elsevier, 2016.

[2] ReliaSoft Corporation, System Analysis Reference: Reliability, Availability & Optimization, 7th ed., Tucson: ReliaSoft Publisher, 2007.

[3] The OREDA Particpants, OREDA 2015, 6 ed., Norway: Published by OREDA participants, 2015.

[4] P. D. O'Connor, D. Newton and R. Bromley, Practical Reliability Engineering, 4th ed., West Sussex: John Wiley & Sons, 2002.

[5] S. Saraswat and G. Yadava, "An overview on reliability, availability, maintainability and supportability (RAMS) engineering," *IJQRM,* vol. 25, no. 3, pp. 330-334, 2008.

[6] K. R. Mobley, Miantenance Engineering Handbook, 8th ed., McGraw-Hill Professional, 2014.

[7] H. D. Goel, "Integrating Reliability, Availability and Maintainability (RAM) in Conceptual Process Design: An Optimization Approach," DUP Science, Delft, 2004.

[8] D. D. Adhikary, G. K. Bose, S. Chattopadhyay, D. Bose and S. Mitra, "RAM investigation of coal-fired thermal plants: A case study," *International Journal of Industrial Engineering Computations,* no. 3, pp. 423-434, 2012.

[9] X. Zou and K. Wang, "Numerical simulations and modeling for stochastic biological systems with jumps," *Communication in Nonlinear Science and Numerical Simulation,* no. 19, pp. 1557-1568, 2014.

[10] C. Henry, J.-P. Minier, M. Mohaupt, C. Profeta, J. Pozorski and A. Tanière, "A stochastic approach for the simulation of collisions between colloidal particles at large time steps," *International Journal of Multiphase Flow,* no. 61, pp. 94-107, 2014.

[11] P. Parthanadee and J. Buddhakulsomsiri, "Production efficiency improvement in batch production system using value stream mapping and simulation: a case study of the roasted and ground coffee industry," *Production Planning & Control,* vol. V, no. 25, pp. 425-446, 2014.

[12] S. Ritter, "Monte Carlo integration – a case-study for simulation," *International Journal of Mathematical Education in Science and Technology,* pp. 131-145, 2013.

[13] S. N. Hojjati and N. R. Noudehi, "The use of Monte Carlo simulation in quantitative risk assessment of IT projects," *International Journal of Advanced Networking & Applications,* vol. 07, no. 01, pp. 2616-2621, 2015.

[14] National Research Council, Assessing the Reliability of Complex Models, Washington, DC: The National Academies Press, 2012.

[15] J. J. Nutaro, J. C. Schryver and M. J. Haire, "The throughput, reliability, availability, maintainability (TRAM) methodology for predicting chemical plant production," Reno, 2012.

[16] Y. Jackson, P. Tabbagh, P. Gibson and E. Seglie, "DoD guide for achieving and assessing Relaibility, Availability, and Maintaiability," Alexandria, 2005.

[17] I. Sutton, Reliability, Availability and Maintainability, Process Risk and Reliability Management, Oxford: William Andrew Publishing, 2010.

[18] J. Banks, Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice, Wiley and Sons, 1998.

[19] W. D. Kelton, R. P. Sadowski and D. T. Sturrock, Simulation with Arena, 6th ed., New York: McGraw-Hill, 2015.

[20] P. S. Rajpal, K. S. Shishodia and G. S. Sekhon, "An artificial neural network for modelling reliability, availability and maintainability of a repairable

system," *Reliability Engineering and System Safety*, vol. 91, no. 7, pp. 809-819, 2006.

[21] M. Meyer, *Stochastic Modelling in the Petrochemical Industry (Discrete Event Simulation Based)*, Potchefstroom: NWU Ferdinand Postma Library, 2004.

[22] R. E. Barlow and F. Proschan, Statistical theory of reliability and life testing: probability models, New York: Holt, Rinehart and Winston, 1975.

[23] C. R. Cassady and E. Kutanoglu, "Integrating preventive maintenance planning and production scheduling for a single machine," *IEEE Transactions on Reliability*, vol. 54, no. 2, pp. 304-309, 2005.

[24] W. Denson, G. Chandler, W. Crowell, A. Clark and P. Jaworski, Non electronic Parts Reliability Data, Wiley Online Library, 1995.

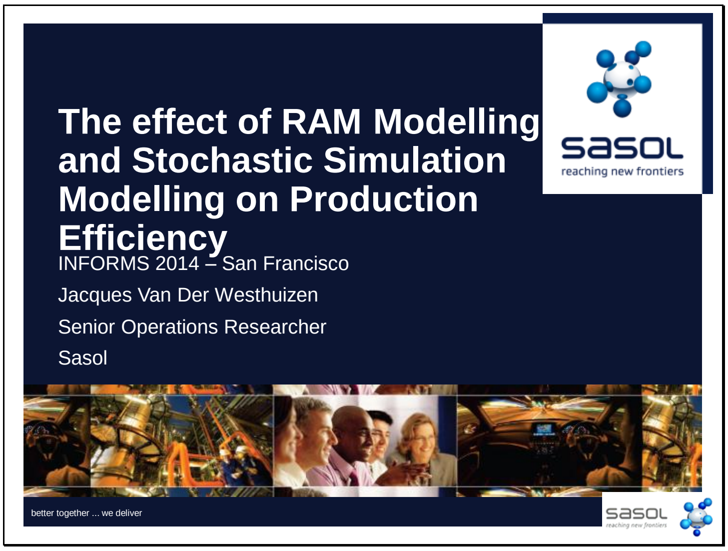
[25] Arnic Research Corporation, Availability analysis handbook for coal gasification and combustion turbine-based power system., Palo Alto: Prepared for Electric Power Research Institute, 1985.

[26] L. Wang, "Production Assurance and Life Cycle Cost Evaluation of Offshore Development Projects in the Conceptual Design Phase," Faculty of Engineering Science and Technology Department of Production and Quality Engineering, Trondheim, 2012.

[27] U. D. Kumar, J. Crocker, J. Knezevic and M. El-Haram, Reliability, Maintenance and Logistic Support - A Life Cycle Approach, London: Kluwer Academic Publishers, 2012.

[28] ReliaSoft Corporation, BLOCKSIM/RENO 10 User's Guide, 10th ed., Tucson: ReliaSoft Publishing, 2016.

Appendix C International Conference Informs



The effect of RAM Modelling and Stochastic Simulation Modelling on Production Efficiency

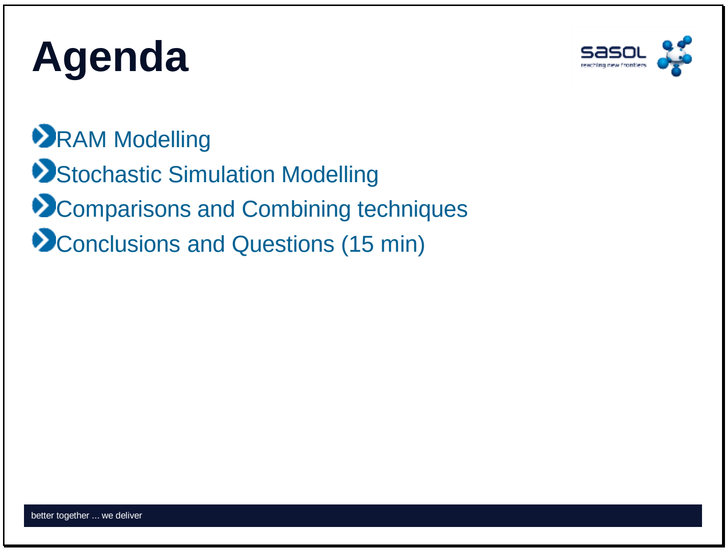
INFORMS 2014 – San Francisco

Jacques Van Der Westhuizen

Senior Operations Researcher

Sasol

better together ... we deliver



Agenda

- RAM Modelling
- Stochastic Simulation Modelling
- Comparisons and Combining techniques
- Conclusions and Questions (15 min)

better together ... we deliver

What is RAM Modelling?

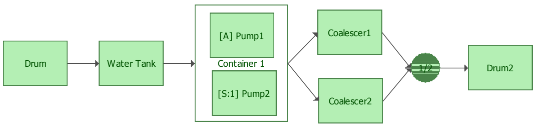
- **RAM Modelling:** Simulation modelling used to predict and analyse the life-cycle of equipment systems in terms of reliability, availability and maintainability. RAM modelling does not provide any volumetric result.
- **Availability:** Availability is the proportion of time a system is in a functioning condition and able to operate. Only the effects of planned shutdowns are taken into account in this calculation
- **Reliability:** The ability of an apparatus, machine, or system to consistently perform its intended or required function or mission, on demand and without degradation or failure. Therefore, the effects of planned shutdowns and unplanned shutdowns (i.e. trips and equipment failures) are included. The initial start-up period of the GTL Plant and ramp up/down times are excluded from this calculation
- **Maintainability**: Assume repair to new, spares are always available

better together ... we deliver

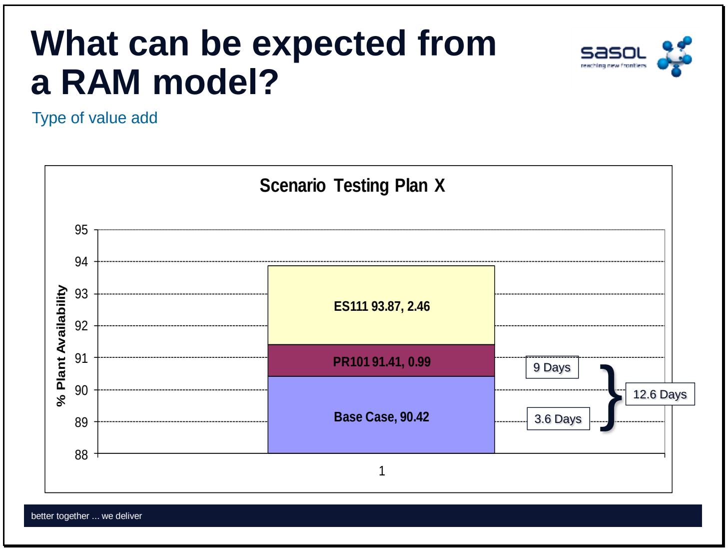
What is unique about a RAM model?

Structure

- Reliability block diagram (RBD) ≠ Process flow diagram
- RBD – Series or parallel relationship depending on redundancy of equipment and failure influence
- RBD – Not focussed on throughput, rather availability of equipment, subsystems and systems



better together ... we deliver



What can be expected from a RAM model?

Type of value add

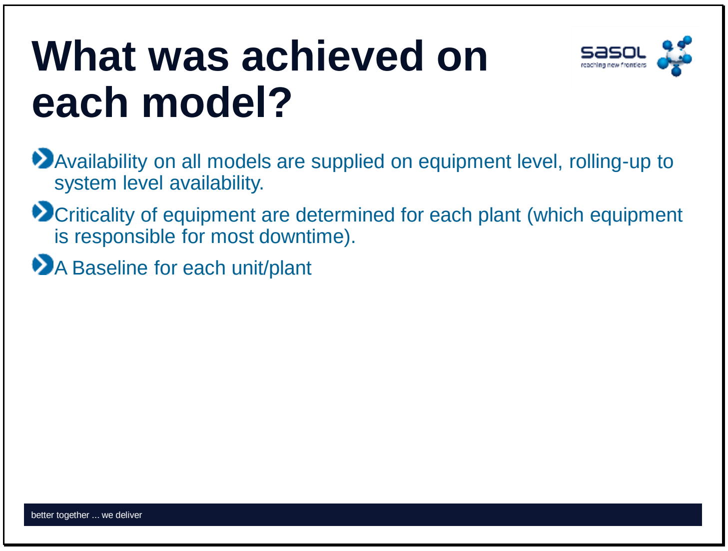
better together ... we deliver

What can be expected from a RAM model?(2)

What is in it for us?

- Design-in reliability for new plants
- Improved decision capability for existing plants
- A tool to assist in business case justification
- A tool to test changes to shutdown philosophies, maintenance strategies, changes in equipment, sparing justification and how does it impact plant availability
- A tool to assist in improving overall equipment and system availability

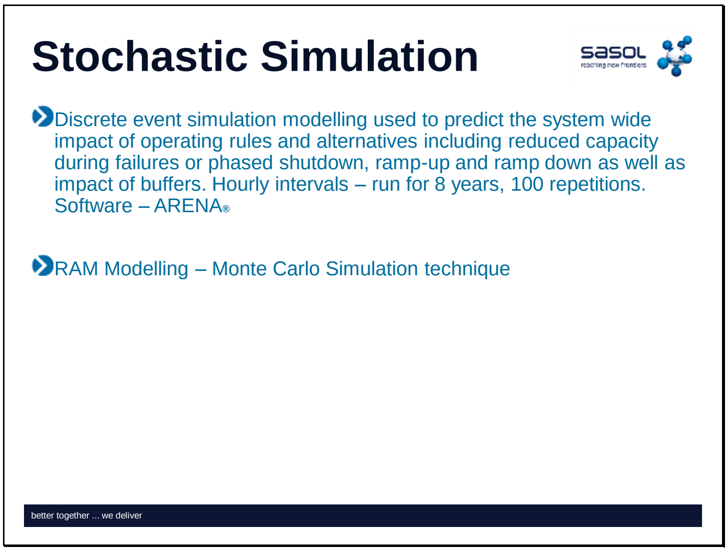
better together ... we deliver



What was achieved on each model?

- Availability on all models are supplied on equipment level, rolling-up to system level availability.
- Criticality of equipment are determined for each plant (which equipment is responsible for most downtime).
- A Baseline for each unit/plant

better together ... we deliver



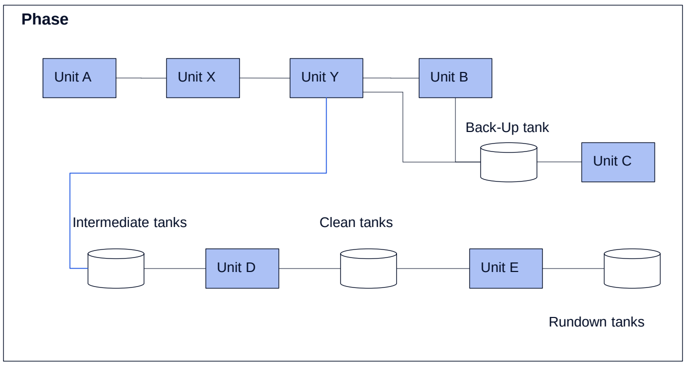
Stochastic Simulation

- Discrete event simulation modelling used to predict the system wide impact of operating rules and alternatives including reduced capacity during failures or phased shutdown, ramp-up and ramp down as well as impact of buffers. Hourly intervals – run for 8 years, 100 repetitions. Software – ARENA®

- RAM Modelling – Monte Carlo Simulation technique

better together ... we deliver

What is Production Efficiency?



Phase

Unit A

Unit X

Unit Y

Unit B

Back-Up tank

Unit C

Intermediate tanks

Clean tanks

Unit D

Unit E

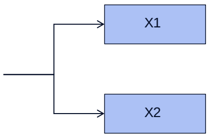
Rundown tanks

RAM Modelling complementing Stochastic Modelling Simulation

A few things to remember

- The RAM modeller and Stochastic Simulation Modeller’s data need to be aligned at all times.
- Validation of ones data and model needs to be done frequently
- The Stochastic Simulation Modeller will need to do a few runs to test the RAM Modeller’s data in other words, is the failures realistic.
- RAM Modelling focus more on detail
- Stochastic Simulation focus at throughput/volume, not so much at the detail

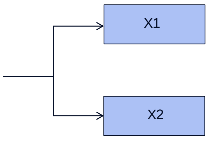
RAM Plant availability calculation – example



Units available	Percentage of the time	Plant available	Availability value
X1 & X2	80	yes	1
X1	8	yes	1
X2	8	yes	1
none	4	no	0

- Plant availability = 80*1+8*1+8*1+4*0 = 96%
- Rule: one unit available – system available

Production Efficiency Calculation



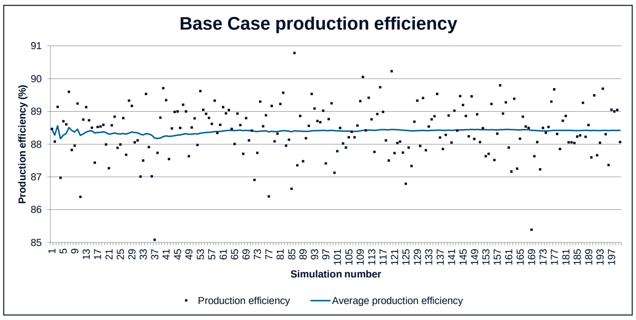
Units available	Percentage of the time	Percentage production	Production efficiency value
X1 & X2	80	100	1
X1	8	50	0.5
X2	8	50	0.5
none	4	0	0

- Production efficiency= 80*1+8*0.5+8*0.5+4*0 = 88%
- No variability included in equation

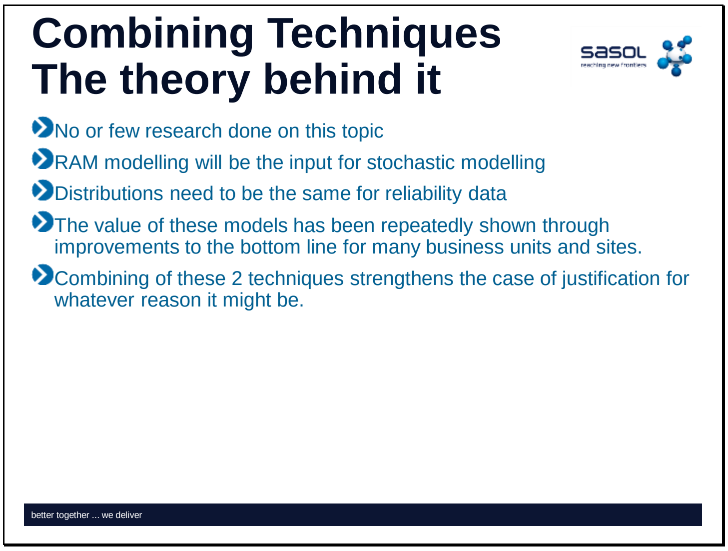
Example of a Base Case Scenario

	Simulation production efficiency	Delta
Reduction start	100%	-
RAM (breakdowns)	94%	6%
Plus shutdowns	90%	4%
Plus ramp up	89.50%	0.50%
Plus tanks – final answer	**88.50%**	1%

Base Case Simulation



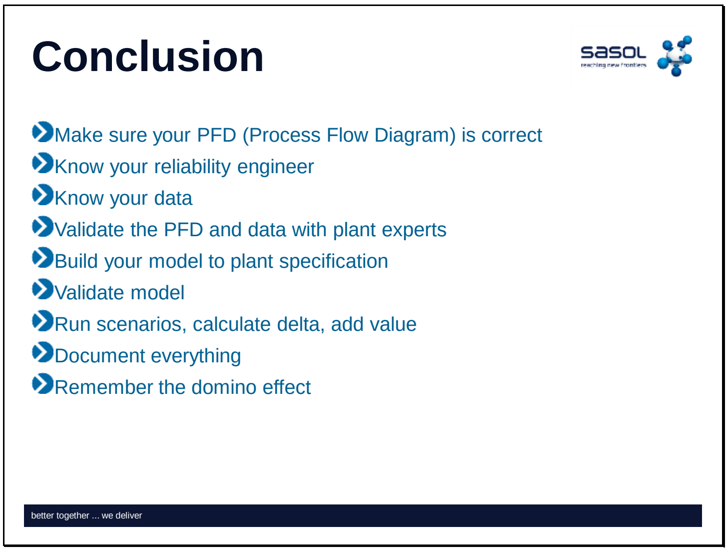
Variation = 5.71%



Combining Techniques
The theory behind it

- No or few research done on this topic
- RAM modelling will be the input for stochastic modelling
- Distributions need to be the same for reliability data
- The value of these models has been repeatedly shown through improvements to the bottom line for many business units and sites.
- Combining of these 2 techniques strengthens the case of justification for whatever reason it might be.

better together ... we deliver

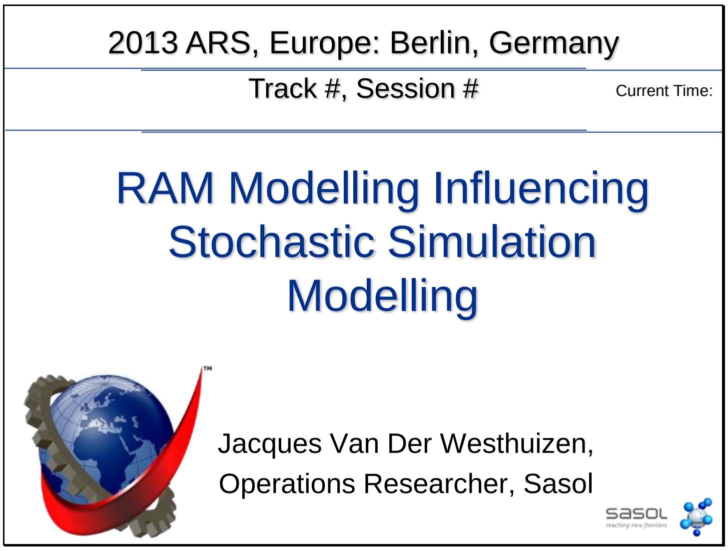


Conclusion

- Make sure your PFD (Process Flow Diagram) is correct
- Know your reliability engineer
- Know your data
- Validate the PFD and data with plant experts
- Build your model to plant specification
- Validate model
- Run scenarios, calculate delta, add value
- Document everything
- Remember the domino effect

better together ... we deliver

Appendix D International Conference ARS



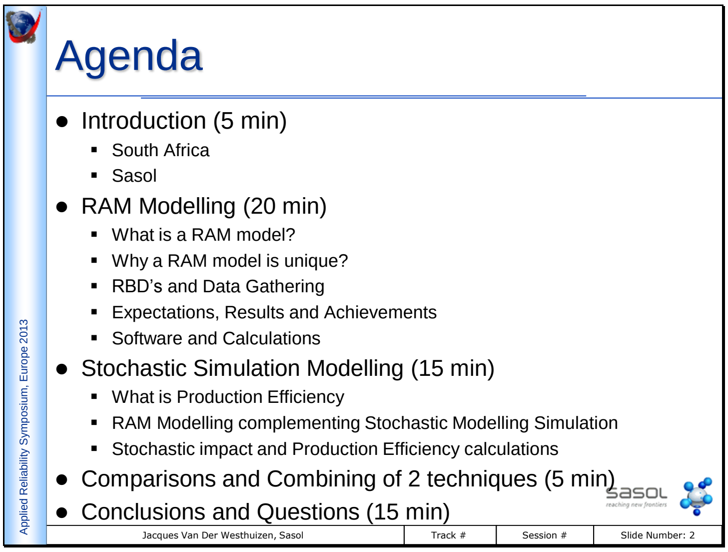
2013 ARS, Europe: Berlin, Germany

Track #, Session #

Current Time:

RAM Modelling Influencing Stochastic Simulation Modelling

Jacques Van Der Westhuizen,
Operations Researcher, Sasol



Applied Reliability Symposium, Europe 2013

Agenda

- Introduction (5 min)
  - South Africa
  - Sasol
- RAM Modelling (20 min)
  - What is a RAM model?
  - Why a RAM model is unique?
  - RBD's and Data Gathering
  - Expectations, Results and Achievements
  - Software and Calculations
- Stochastic Simulation Modelling (15 min)
  - What is Production Efficiency
  - RAM Modelling complementing Stochastic Modelling Simulation
  - Stochastic impact and Production Efficiency calculations
- Comparisons and Combining of 2 techniques (5 min)
- Conclusions and Questions (15 min)

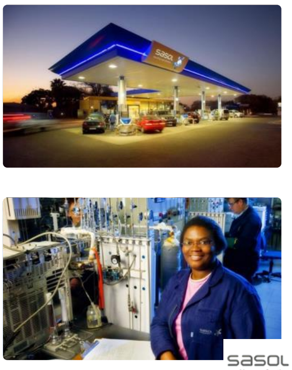
Jacques Van Der Westhuizen, Sasol | Track # | Session # | Slide Number: 2

Background – South Africa

- Population +- 50 million people
- 11 Official Languages
- Table Mountain on World Monopoly
- Fastest land animal – cheetah – from 0 mph to 60 mph in 2.5 seconds. Can reach speeds up to 75 mph. Faster than any motor vehicle from 0 to 60 mph. Usain Bolt 100 m 9.58 s. A Cheetah run the 100 m in 5.9 s.
- Nelson Mandela became president in 1994. Spent 27 years in jail because of Apartheid.

Background - Sasol

- World’s largest supplier of synthetic fuels and chemicals
- One of the top 5 publicly listed companies in SA
- National GDP contribution: 4.71%
- 250 PhD’s (the most for any company in the southern hemisphere)
- 24th: *Business Week’s* “World's Best Companies, 2009”

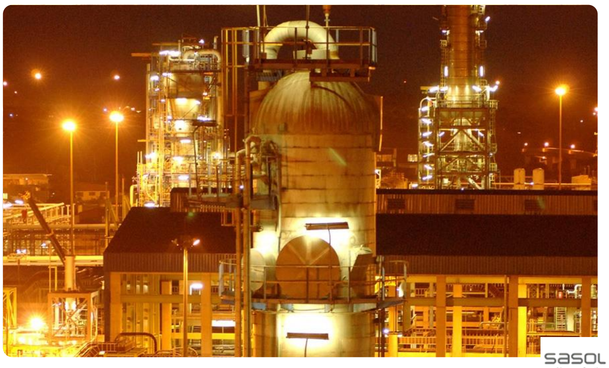


Secunda Complex

Secunda Stats

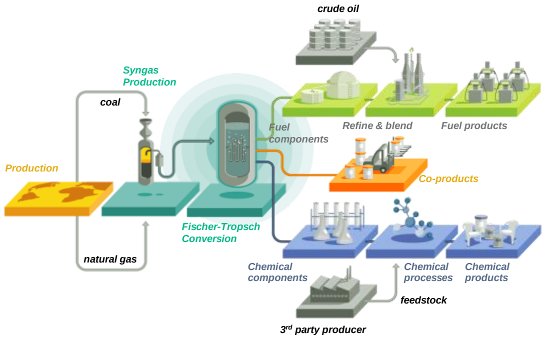
- **Power consumption:**
  - 1,300 MW = 25% of NYC
- **Coal consumption/day:**
  - 243 million pounds = 2,340 railcars/day
- **Area:**
  - 5 square miles = 2,090 football fields
- **Purified oxygen production:**
  - 84 million pounds/day = space shuttle’s launch requirements in 25 minutes!
- **Liquid fuels and chemicals production/day:**
  - 6.7 million gallons

Fischer – Tropsch Reactor



sasol reaching new frontiers

Our Value Chain



sasol reaching new frontiers

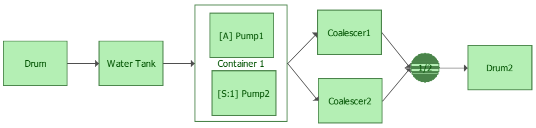
What is RAM Modelling

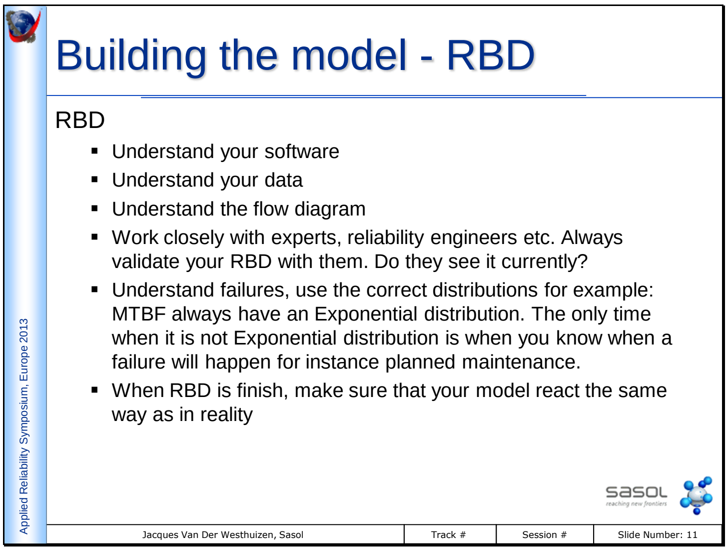
- **RAM Modelling:** Simulation modelling used to predict and analyse the life-cycle of equipment systems in terms of reliability, availability and maintainability. RAM modelling does not provide any volumetric result.
- **Availability:** Availability is the proportion of time a system is in a functioning condition and able to operate. Only the effects of planned shutdowns are taken into account in this calculation
- **Reliability:** The ability of an apparatus, machine, or system to consistently perform its intended or required function or mission, on demand and without degradation or failure. Therefore, the effects of planned shutdowns and unplanned shutdowns (i.e. trips and equipment failures) are included. The initial start-up period of the GTL Plant and ramp up/down times are excluded from this calculation
- **Maintainability**: Assume repair to new

What is unique about a RAM model?

Structure

- Reliability block diagram (RBD) ≠ Process flow diagram
- RBD – Series or parallel relationship depending on redundancy of equipment and failure influence
- RBD – Not focussed on throughput, rather availability of equipment, subsystems and systems

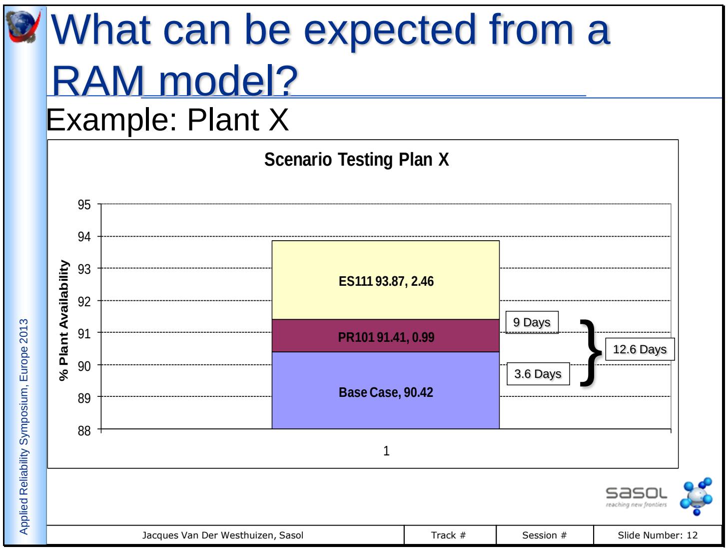




Building the model - RBD

RBD

- Understand your software
- Understand your data
- Understand the flow diagram
- Work closely with experts, reliability engineers etc. Always validate your RBD with them. Do they see it currently?
- Understand failures, use the correct distributions for example: MTBF always have an Exponential distribution. The only time when it is not Exponential distribution is when you know when a failure will happen for instance planned maintenance.
- When RBD is finish, make sure that your model react the same way as in reality



What can be expected from a RAM model?

Example: Plant X

What can be expected from a RAM model?(2)

What is in it for us?

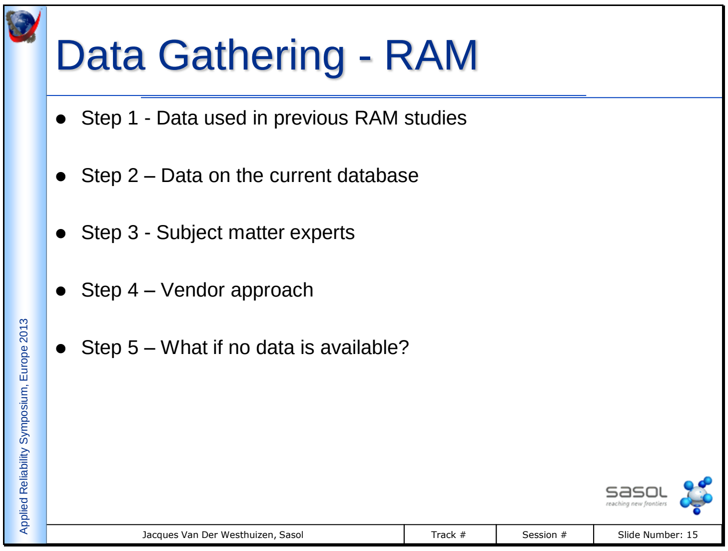
- Design-in reliability for new plants
- Improved decision capability for existing plants
- A tool to assist in business case justification
- A tool to test changes to shutdown philosophies, maintenance strategies, changes in equipment, sparing justification and how does it impact plant availability
- A tool to assist in improving overall equipment and system availability

---

What can be expected from a RAM model? (Software)

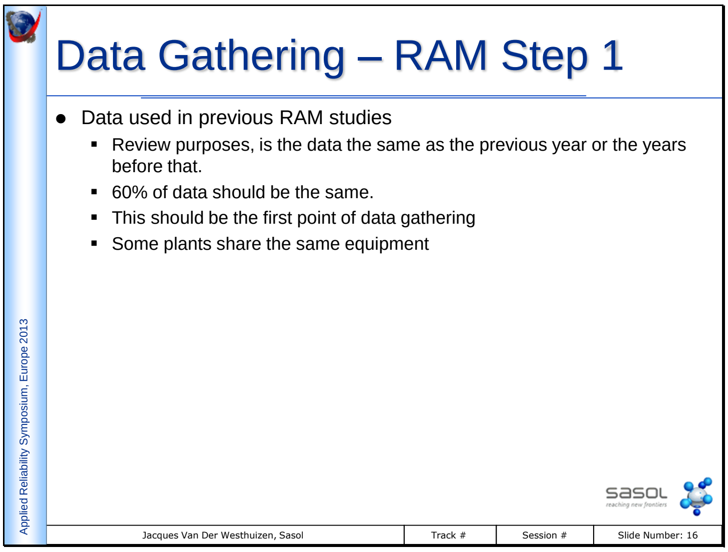
Software Functionality

- In a Single Model, the software captures all of the following:
  - o Design of the System
  - o Reliability of the Components
  - o Operational scenarios
  - o Logistics Infrastructure
  - o Spares Strategy
  - o Maintenance Policies
  - o … and the complex interactions between them
- Extensions to Monte Carlo Technology
  - o Asset performance
  - o Component aging and full or partial rejuvenation by repair
  - o Custom Logic in response to events
- Insightful Outputs
  - o Availability/Reliability
  - o Sensitivity - Contributor to Lost Performance
  - o User-Defined Outputs



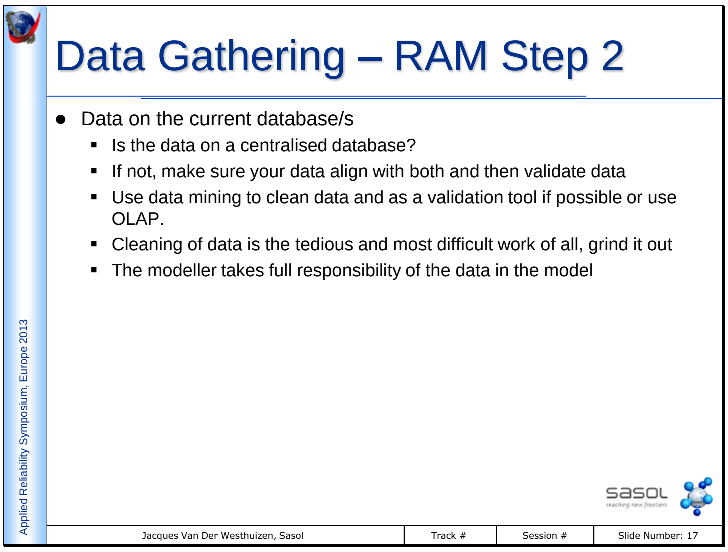
Data Gathering - RAM

- Step 1 - Data used in previous RAM studies
- Step 2 – Data on the current database
- Step 3 - Subject matter experts
- Step 4 – Vendor approach
- Step 5 – What if no data is available?



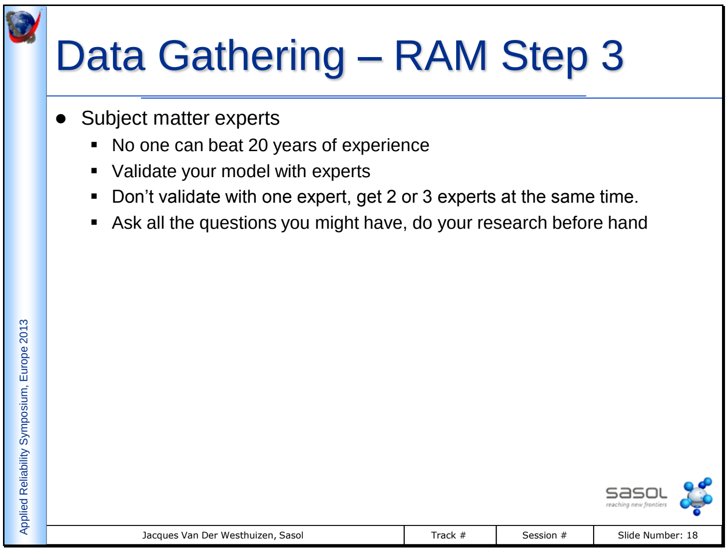
Data Gathering – RAM Step 1

- Data used in previous RAM studies
  - Review purposes, is the data the same as the previous year or the years before that.
  - 60% of data should be the same.
  - This should be the first point of data gathering
  - Some plants share the same equipment



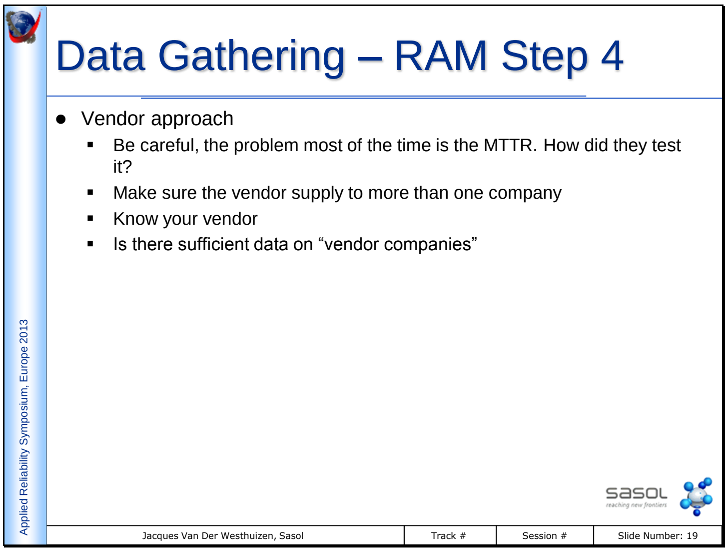
Data Gathering – RAM Step 2

- Data on the current database/s
  - Is the data on a centralised database?
  - If not, make sure your data align with both and then validate data
  - Use data mining to clean data and as a validation tool if possible or use OLAP.
  - Cleaning of data is the tedious and most difficult work of all, grind it out
  - The modeller takes full responsibility of the data in the model



Data Gathering – RAM Step 3

- Subject matter experts
  - No one can beat 20 years of experience
  - Validate your model with experts
  - Don’t validate with one expert, get 2 or 3 experts at the same time.
  - Ask all the questions you might have, do your research before hand

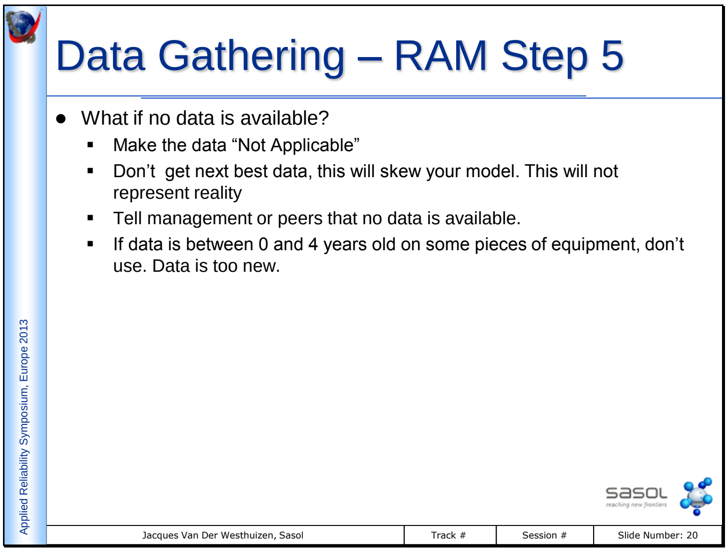


Data Gathering – RAM Step 4

- Vendor approach
  - Be careful, the problem most of the time is the MTTR. How did they test it?
  - Make sure the vendor supply to more than one company
  - Know your vendor
  - Is there sufficient data on “vendor companies”

Applied Reliability Symposium, Europe 2013

Jacques Van Der Westhuizen, Sasol | Track # | Session # | Slide Number: 19



Data Gathering – RAM Step 5

- What if no data is available?
  - Make the data “Not Applicable”
  - Don’t get next best data, this will skew your model. This will not represent reality
  - Tell management or peers that no data is available.
  - If data is between 0 and 4 years old on some pieces of equipment, don’t use. Data is too new.

Applied Reliability Symposium, Europe 2013

Jacques Van Der Westhuizen, Sasol | Track # | Session # | Slide Number: 20

What was achieved on each model?

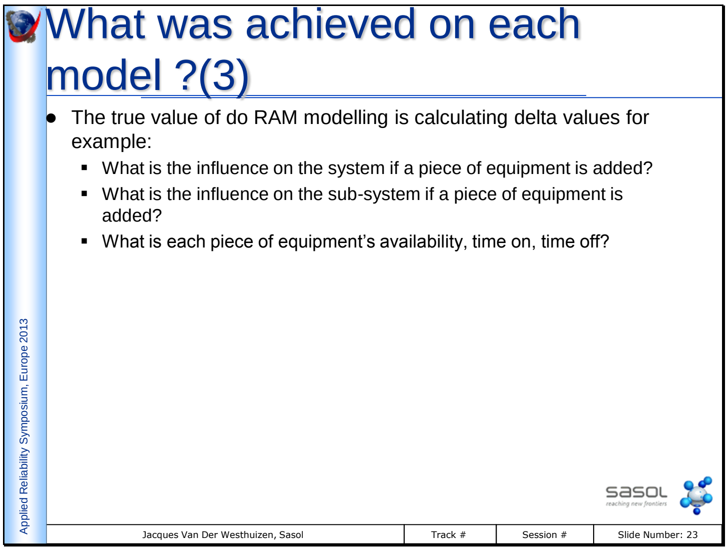
- Availability on all models are supplied on equipment level, rolling-up to system level availability.
- Criticality of equipment are determined for each plant (which equipment is responsible for most downtime).
- A Baseline for each unit/plant

sasol reaching new frontiers

What was achieved on each model ?(2)

- Scenarios can and were tested for plant availability under different conditions.
- Improved maintenance philosophies
- Business cases for additional equipment
- Impact of scrubbing

sasol reaching new frontiers

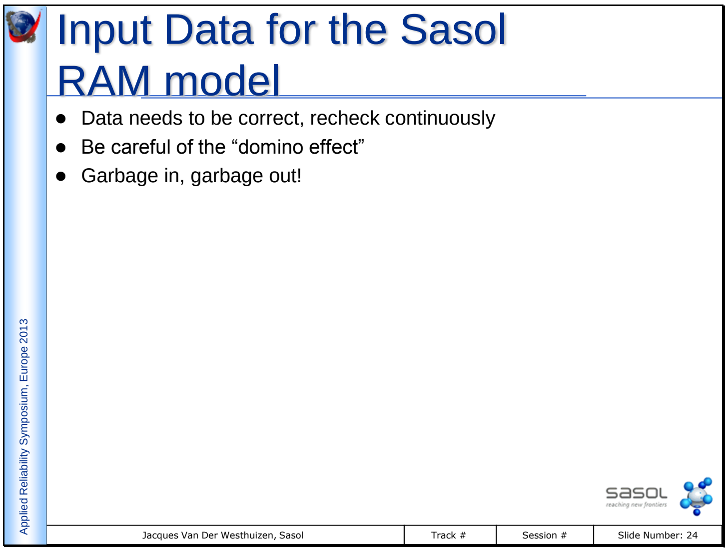


Applied Reliability Symposium, Europe 2013

What was achieved on each model ?(3)

- The true value of do RAM modelling is calculating delta values for example:
    - What is the influence on the system if a piece of equipment is added?
    - What is the influence on the sub-system if a piece of equipment is added?
    - What is each piece of equipment's availability, time on, time off?

Jacques Van Der Westhuizen, Sasol	Track #	Session #	Slide Number: 23



Applied Reliability Symposium, Europe 2013

Input Data for the Sasol RAM model

- Data needs to be correct, recheck continuously
- Be careful of the “domino effect”
- Garbage in, garbage out!

Jacques Van Der Westhuizen, Sasol	Track #	Session #	Slide Number: 24

Input data for the Sasol RAM model – comparison of Example Unit X

	MTBF			MTTR			MTBF			MTTR		
Equipment Name	**Distr**	**Mean**	**Std. Dev**	**Distr**	**Mean**	**Std. Dev**	**Distr**	**Mean**	**Std. Dev**	**Distr**	**Mean**	**Std. Dev**
A	EXP	8760	N/A	NOR	72	7.2	EXP	12338	N/A	NOR	42	🟥
B	EXP	8760	N/A	NOR	72	7.2	EXP	12338	N/A	NOR	42	🟥
C	EXP	613200	N/A	NOR	360	36	EXP	1752000	N/A	NOR	36	🟥
D	EXP	613200	N/A	NOR	360	36	EXP	1752000	N/A	NOR	36	🟥
E	EXP	8760	N/A	NOR	72	7.2	EXP	12338	N/A	NOR	42	🟥
F	EXP	8760	N/A	NOR	72	7.2	EXP	12338	N/A	NOR	42	🟥
G	EXP	613200	N/A	NOR	360	36	EXP	1752000	N/A	NOR	36	🟥
H	EXP	175200	N/A	NOR	360	36	EXP	569400	N/A	NOR	36	🟥
I	EXP	175200	N/A	NOR	360	36	EXP	569400	N/A	NOR	36	🟥
J	EXP	613200	N/A	NOR	360	36	EXP	1752000	N/A	NOR	36	🟥
K	EXP	175200	N/A	NOR	360	36	EXP	569400	N/A	NOR	36	🟥
L	EXP	8760	N/A	NOR	72	7.2	EXP	12338	N/A	NOR	42	🟥
M	EXP	8760	N/A	NOR	72	7.2	EXP	12338	N/A	NOR	42	🟥
N	EXP	613200	N/A	NOR	360	36	EXP	1752000	N/A	NOR	36	🟥
O	EXP	613200	N/A	NOR	360	36	EXP	1752000	N/A	NOR	36	🟥
P	EXP	613200	N/A	NOR	360	36	EXP	1752000	N/A	NOR	36	🟥
Q	EXP	8760	N/A	NOR	72	7.2	EXP	12338	N/A	NOR	42	🟥
R	EXP	8760	N/A	NOR	72	7.2	EXP	12338	N/A	NOR	42	🟥
S	EXP	613200	N/A	NOR	360	36	EXP	1752000	N/A	NOR	36	🟥
T	EXP	8760	N/A	NOR	72	7.2	EXP	12338	N/A	NOR	42	🟥
U	EXP	8760	N/A	NOR	72	7.2	EXP	12338	N/A	NOR	42	🟥
V	EXP	8760	N/A	NOR	72	7.2	EXP	12338	N/A	NOR	42	🟥
W	EXP	8760	N/A	NOR	72	7.2	EXP	12338	N/A	NOR	42	🟥
X	EXP	613200	N/A	NOR	360	36	EXP	1752000	N/A	NOR	36	🟥

- MTBF: Mean time between failures (Average time for unavailable equipment)
- MTTR: Mean time to repair
- Assumption std deviation of 10%

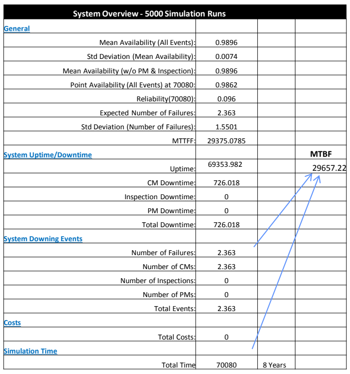
sasol
reaching new frontiers

Input data – few things noted

- Data from 2 sources might be very different
- Data companies assume you know the type of data they use
- Failures differ from company to company. Why?
- Be careful of outsourcing/ in sourcing consultants
- If using consultants make sure they know your plant, company, data, software and evidently the failures.

sasol
reaching new frontiers

MTBF calculated for Unit X



System Overview - 5000 Simulation Runs			
General			
Mean Availability (All Events):	0.9896		
Std Deviation (Mean Availability):	0.0074		
Mean Availability (w/o PM & Inspection):	0.9896		
Point Availability (All Events) at 70080:	0.9862		
Reliability(70080):	0.096		
Expected Number of Failures:	2.363		
Std Deviation (Number of Failures):	1.5501		
MTTFF:	29375.0785		
System Uptime/Downtime			**MTBF**
Uptime:	69353.982		29657.22
CM Downtime:	726.018		
Inspection Downtime:	0		
PM Downtime:	0		
Total Downtime:	726.018		
System Downing Events			
Number of Failures:	2.363		
Number of CMs:	2.363		
Number of Inspections:	0		
Number of PMs:	0		
Total Events:	2.363		
Costs			
Total Costs:	0		
Simulation Time			
Total Time	70080	8 Years	

- MTBF Calculated:
  - =Total time / No. of failures
  - =70080 / 2.363
  - 29657.22

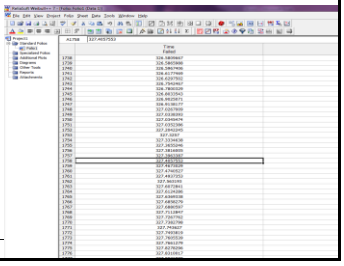
sasol
reaching new frontiers

MTTR calculated for Unit X (1)

- A text file is generated for each unit after 5000 simulation runs
- Each simulation has Total Downtime and Number of Failures calculated.
- MTTR = Total Downtime / Number of Failures
- Example

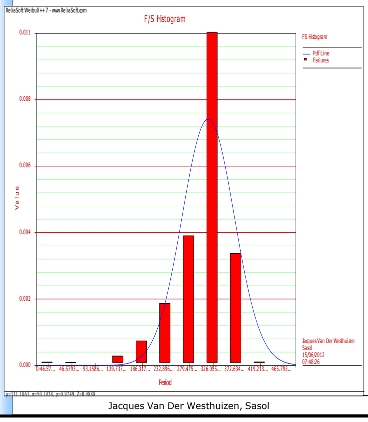
Seed	Total Downtime	Number of Failures	MTTR
1	1459.93139	6	243.3219
2	2183.304313	6	363.8841
3	1425.217208	4	356.3043
4	2127.677685	6	354.6129
5	2460.153664	8	307.5192
6	1393.952701	4	348.4882
7	1780.631831	5	356.1264
8	1494.69697	4	373.6742
9	1075.996943	3	358.6656
10	940.1978477	3	313.3993

- ***5000 MTTR points created distribution fitted using Reliasoft Weibull++®***



Applied Reliability Symposium, Europe 2013

MTTR calculated for Unit X (2)



- MTTR:

Normal Distribution

Mean = 331.186

Std Dev = 50.193

sasol
reaching new frontiers

Jacques Van Der Westhuizen, Sasol	Track #	Session #	Slide Number: 29

Applied Reliability Symposium, Europe 2013

Calculations

- When calculating the availability of a plant, getting results for biggest contributors of downtime ALWAYS validate against what you see in reality. Ask field experts, no one can beat 20 years of experience.
- MTBF and MTTR are the foundation on which RAM modelling are build on, make sure it is correct.
- All units used must be the same, if hours are used, the whole project should be in hours.
- Do a Goodness-of-fit test for distributions. This is just a guideline not cast in stone.

sasol
reaching new frontiers

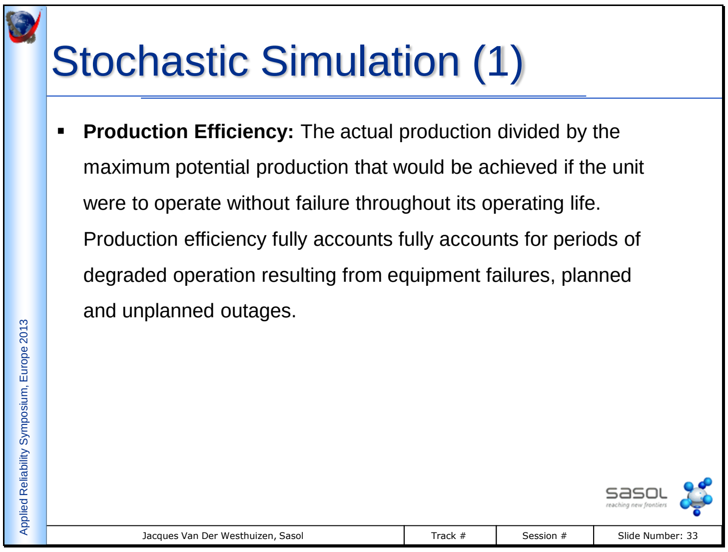
Jacques Van Der Westhuizen, Sasol	Track #	Session #	Slide Number: 30

Calculations (2)

- Uptime and downtime of the system and equipment is a good validation.
- If the model is configure correctly, uptime and downtime of the overall plant or equipment could be a very good indicator of how well the plant is running.
- If downtime contributors in the model agrees with reality, it could be used for justification for future products.

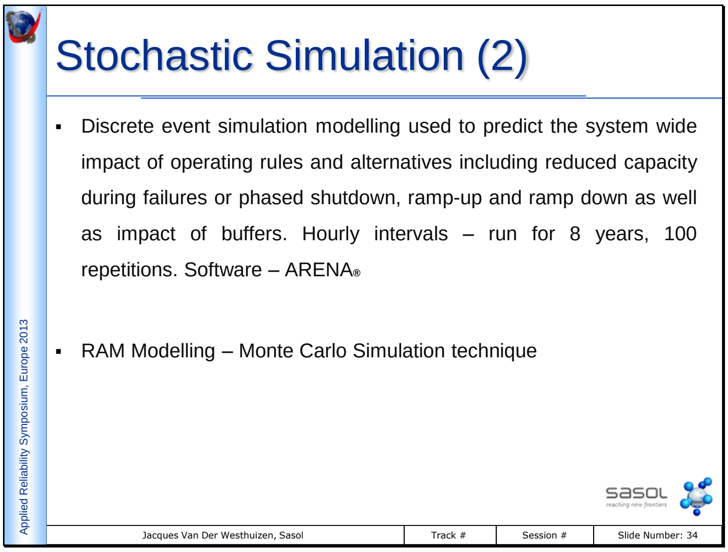
RAM Modelling conclusion

- Make sure of your data, remember the rule: “garbage in garbage out”.
- Know your data, know your software and know your field experts.
- Units need to be the same
- Make sure you don’t double dip any where, planned maintenance is usually the culprit.



Stochastic Simulation (1)

- **Production Efficiency:** The actual production divided by the maximum potential production that would be achieved if the unit were to operate without failure throughout its operating life. Production efficiency fully accounts fully accounts for periods of degraded operation resulting from equipment failures, planned and unplanned outages.



Stochastic Simulation (2)

- Discrete event simulation modelling used to predict the system wide impact of operating rules and alternatives including reduced capacity during failures or phased shutdown, ramp-up and ramp down as well as impact of buffers. Hourly intervals – run for 8 years, 100 repetitions. Software – ARENA®

- RAM Modelling – Monte Carlo Simulation technique

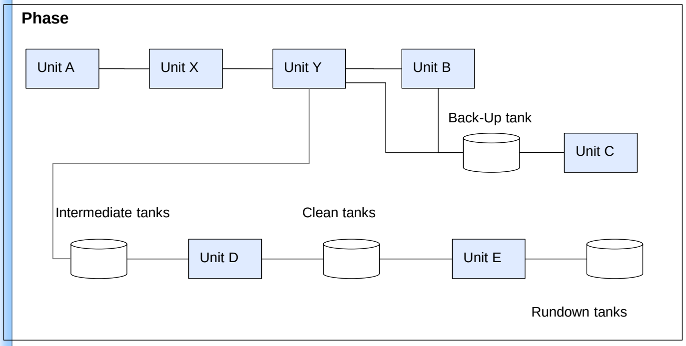
Stochastic Simulation (3)

- The crux of the whole exercise is this:
  - Use failure distributions (MTBF, MTTR) that were calculated as an input to the Production efficiency model.

- Just a note that if your model is finished and you need to change just one piece of equipment value then the whole model will change. It is very important

---

What is Production Efficiency?

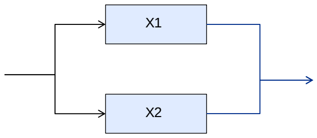


RAM Modelling complementing Stochastic Modelling Simulation

- A few things to remember:
  - The RAM modeller and Stochastic Simulation Modeller's data need to be aligned at all times.
  - Validation of ones data and model needs to be done frequently
  - The Stochastic Simulation Modeller will need to do a few runs to test the RAM Modeller's data in other words, is the failures realistic.
  - RAM Modelling focus more on detail
  - Stochastic Simulation focus at throughput/volume, not so much at the detail

---

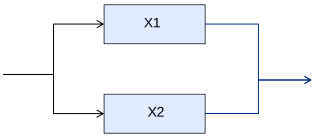
RAM Plant availability calculation - example



Units available	Percentage of the time	Plant available	Availability value
X1 & X2	80	yes	1
X1	8	yes	1
X2	8	yes	1
none	4	no	0

- Plant availability = 80*1+8*1+8*1+4*0 = 96%
- Rule: one unit available – system available

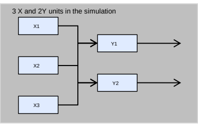
Production Efficiency Calculation



Units available	Percentage of the time	Percentage production	Production efficiency value
X1 & X2	80	100	1
X1	8	50	0.5
X2	8	50	0.5
none	4	0	0

- Production efficiency= 80*1+8*0.5+8*0.5+4*0 = 88%
- No variability included in equation

Stochastic impact on phase simulation results



	RAM value	Stochastic value
X availability	97.38%	97.45%
Y availability	97.53%	97.56%

Theoretical Production efficiency value

- Only breakdowns = 97.45*0.9756 = 95.07%

add Shutdowns		96.17%

28 Days shutdown every 2 years

Theoretical Production efficiency value

- Plus Shutdowns = 95.07*0.9617 = 91.43%

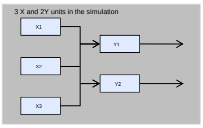
add ramp up		99.38%

3 and 6 Days ramp up every 4 years

Theoretical Production efficiency value

- Plus Ramp up = 91.43*0.9938 = 90.86%

Stochastic part of phase simulation results



	Simulation production efficiency
Only breakdowns	95.12%
Plus Shutdowns & ramp up	90.88%

Theoretical Production efficiency values

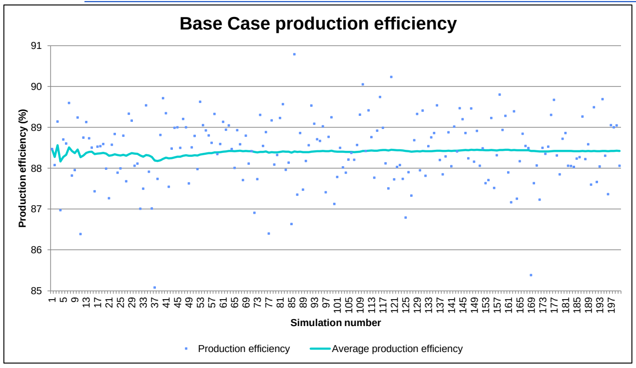
- Only breakdowns = 95.07%
- Plus Shutdowns and ramp up = 90.86%

Base case scenario results - Main scenario

	Simulation production efficiency	Delta
Only breakdowns	94.21%	
Plus Shutdowns	90.04%	4.17%
Plus ramp up	89.93%	0.11%
Plus tanks	88.41%	1.52%

- Tanks assumed at unlimited volume (no constraint)
- Volume loss included in each of the above figures

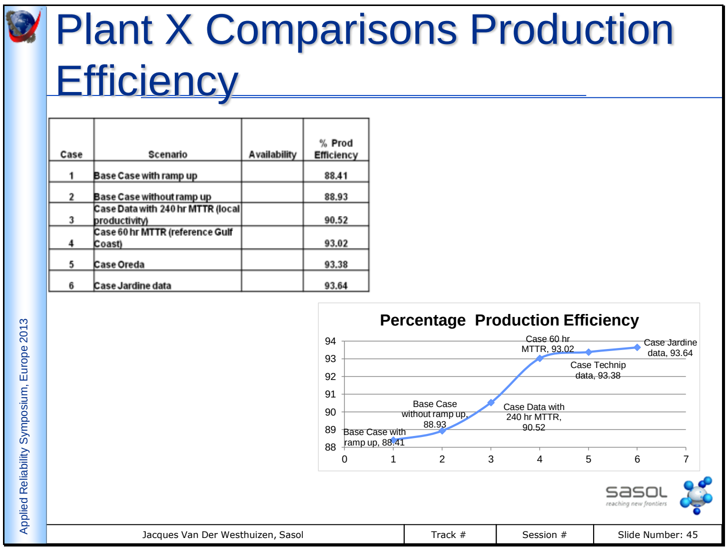
Base case simulation



Variation = 5.71%

RAM Comparison - Scenarios

	Base Case				210 Case				60 Case				Jardine Case			
Base Case	Availability	MTBF Mean (y)	MTTR Mean (d)	Total Downtime (d)	Availability	MTBF Mean (y)	MTTR Mean (d)	Total Downtime (d)	Availability	MTBF Mean (y)	MTTR Mean (d)	Total Downtime (d)	Availability	MTBF Mean (y)	MTTR Mean (d)	Total Downtime (d)
Unit A	99.59	1.7	2.6	12.1	99.7	1.7	1.9	8.8	99.81	1.7	1.2	5.4	99.86	0.6	0.3	4.2
Unit X	97.39	0.8	7.5	76.6	98.28	0.8	4.8	50.2	99.21	0.8	2.2	23.1	99.8	0.6	0.4	5.7
Unit Y	97.52	0.8	7.6	72.1	98.25	0.8	5.3	51.1	98.98	0.8	3.1	29.9	99.01	0.3	1.1	28.8
Unit B	98.14	1.1	7.5	54.9	98.8	1.1	4.9	35.1	99.45	1.1	2.2	16.0	99.7	0.3	0.3	8.7
Unit C	99.74	8.0	15.0	7.6	99.85	15.6	8.7	4.5	99.96	15.6	2.5	1.3	99.99	203.0	1.4	0.1
Unit D	99.88	8.0	15.0	3.5	99.93	34.3	8.8	2.0	99.98	34.3	2.5	0.6	99.99	103.4	1.5	0.1
Unit E	99.22	1.2	3.4	22.8	99.37	1.2	2.7	18.4	99.51	1.2	2.1	14.2	99.98	18.0	0.5	0.5
Unit F	98.96	3.4	12.8	30.3	99.38	3.3	7.6	18.2	99.81	3.3	2.3	5.6	99.97	11.8	1.4	1.0
Phase1	95.51			131.0	97.07			85.4	98.63			40.0	99.4			17.6
Phase2	95.51			131.0	97.07			85.4	98.63			40.0	99.4			17.6
Overall	97.56			71.3	98			58.3	98.38			47.3	98.42			46.3



Applied Reliability Symposium, Europe 2013

Plant X Comparisons Production Efficiency

Case	Scenario	Availability	% Prod Efficiency
1	Base Case with ramp up		88.41
2	Base Case without ramp up		88.93
3	Case Data with 240 hr MTTR (local productivity)		90.52
4	Case 60 hr MTTR (reference Gulf Coast)		93.02
5	Case Oreda		93.38
6	Case Jardine data		93.64

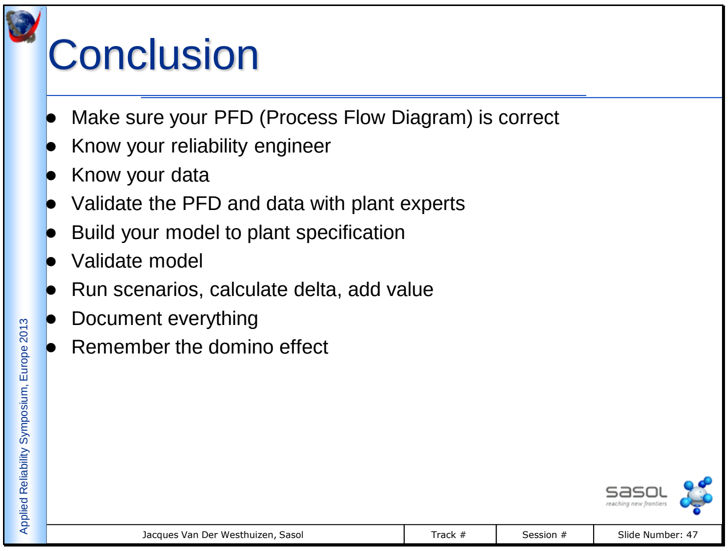
Jacques Van Der Westhuizen, Sasol	Track #	Session #	Slide Number: 45

Applied Reliability Symposium, Europe 2013

Combining 2 techniques - Theory

- No or few research done on this topic
- RAM modelling will be the input for stochastic modelling
- The value of these models has been repeatedly shown through improvements to the bottom line for many business units and sites.
- Combining of these 2 techniques strengthens the case of justification for whatever reason it might be.

Jacques Van Der Westhuizen, Sasol	Track #	Session #	Slide Number: 46

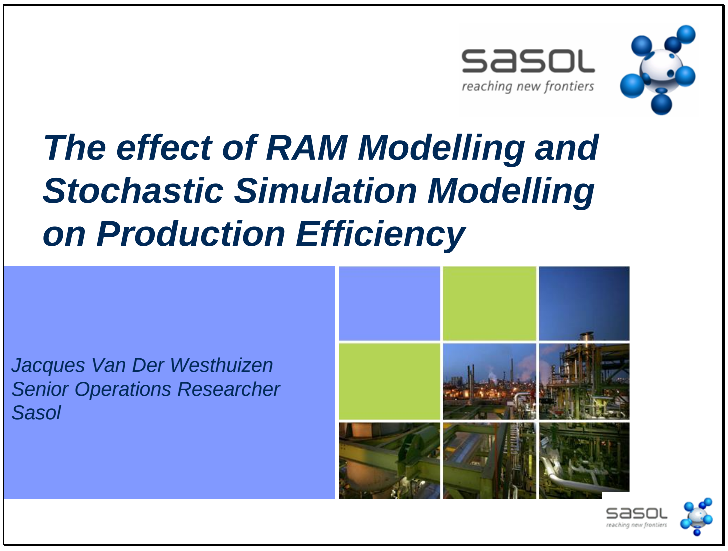


Conclusion

- Make sure your PFD (Process Flow Diagram) is correct
- Know your reliability engineer
- Know your data
- Validate the PFD and data with plant experts
- Build your model to plant specification
- Validate model
- Run scenarios, calculate delta, add value
- Document everything
- Remember the domino effect

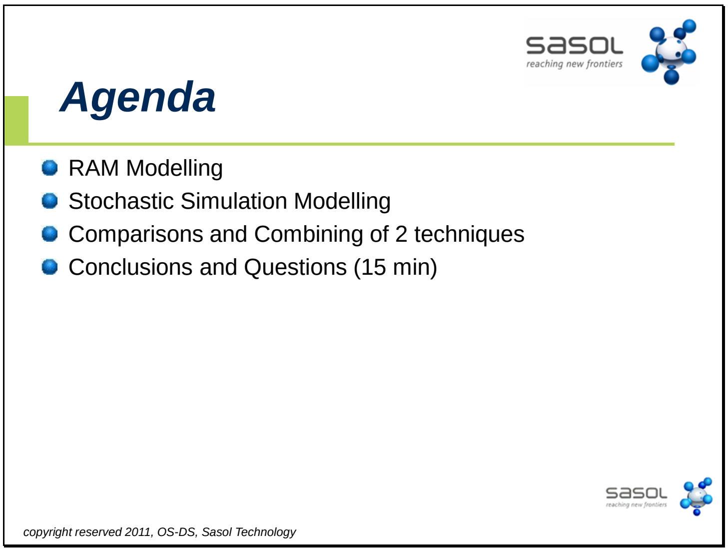
Applied Reliability Symposium, Europe 2013

Appendix E National Conference ORSSA



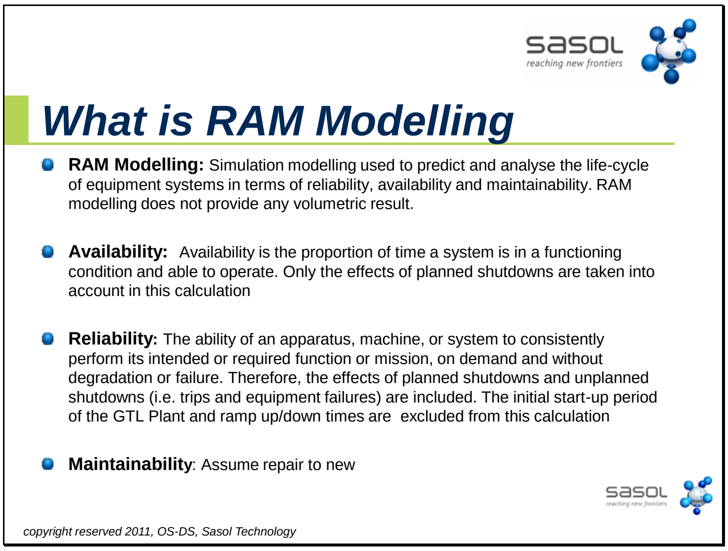
The effect of RAM Modelling and Stochastic Simulation Modelling on Production Efficiency

Jacques Van Der Westhuizen
Senior Operations Researcher
Sasol



Agenda

- RAM Modelling
- Stochastic Simulation Modelling
- Comparisons and Combining of 2 techniques
- Conclusions and Questions (15 min)



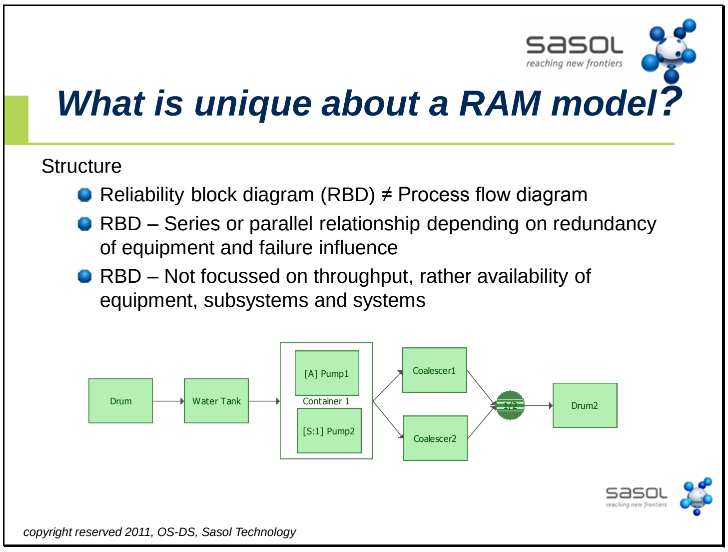
What is RAM Modelling

- **RAM Modelling:** Simulation modelling used to predict and analyse the life-cycle of equipment systems in terms of reliability, availability and maintainability. RAM modelling does not provide any volumetric result.

- **Availability:** Availability is the proportion of time a system is in a functioning condition and able to operate. Only the effects of planned shutdowns are taken into account in this calculation

- **Reliability:** The ability of an apparatus, machine, or system to consistently perform its intended or required function or mission, on demand and without degradation or failure. Therefore, the effects of planned shutdowns and unplanned shutdowns (i.e. trips and equipment failures) are included. The initial start-up period of the GTL Plant and ramp up/down times are excluded from this calculation

- **Maintainability**: Assume repair to new

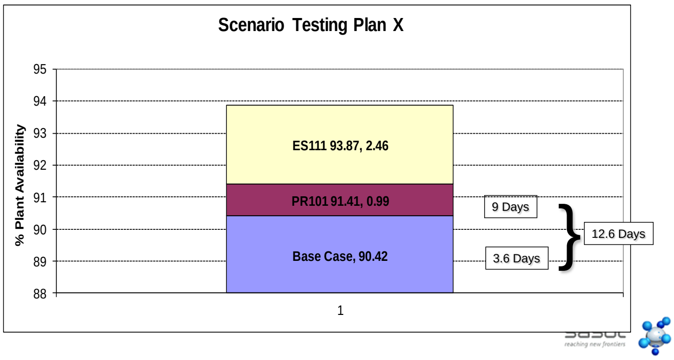


What is unique about a RAM model?

Structure

- Reliability block diagram (RBD) ≠ Process flow diagram
- RBD – Series or parallel relationship depending on redundancy of equipment and failure influence
- RBD – Not focussed on throughput, rather availability of equipment, subsystems and systems

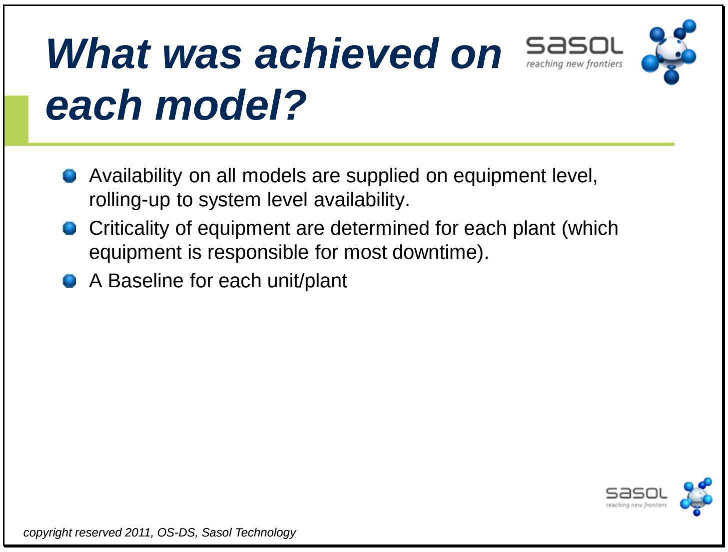
What can be expected from a RAM model?



What can be expected from a RAM model?(2)

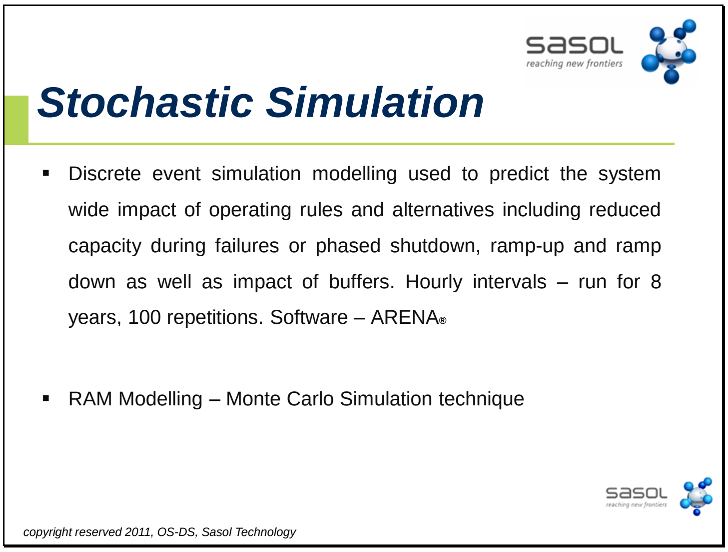
What is in it for us?

- Design-in reliability for new plants
- Improved decision capability for existing plants
- A tool to assist in business case justification
- A tool to test changes to shutdown philosophies, maintenance strategies, changes in equipment, sparing justification and how does it impact plant availability
- A tool to assist in improving overall equipment and system availability



What was achieved on each model?

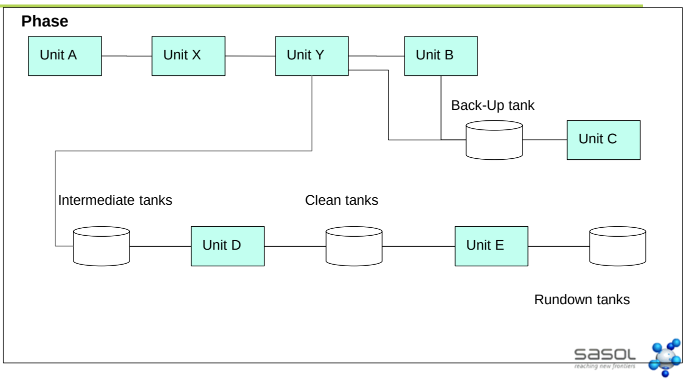
- Availability on all models are supplied on equipment level, rolling-up to system level availability.
- Criticality of equipment are determined for each plant (which equipment is responsible for most downtime).
- A Baseline for each unit/plant



Stochastic Simulation

- Discrete event simulation modelling used to predict the system wide impact of operating rules and alternatives including reduced capacity during failures or phased shutdown, ramp-up and ramp down as well as impact of buffers. Hourly intervals – run for 8 years, 100 repetitions. Software – ARENA®
- RAM Modelling – Monte Carlo Simulation technique

What is Production Efficiency?



Phase

Unit A

Unit X

Unit Y

Unit B

Back-Up tank

Unit C

Intermediate tanks

Clean tanks

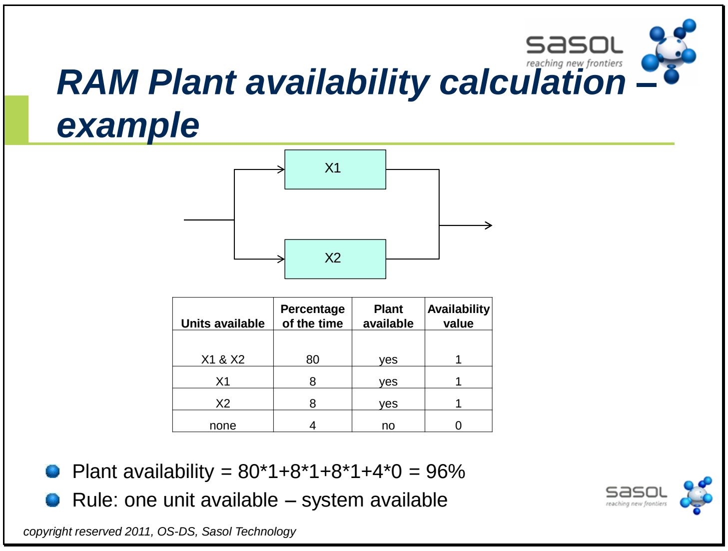
Unit D

Unit E

Rundown tanks

RAM Modelling complementing Stochastic Modelling Simulation

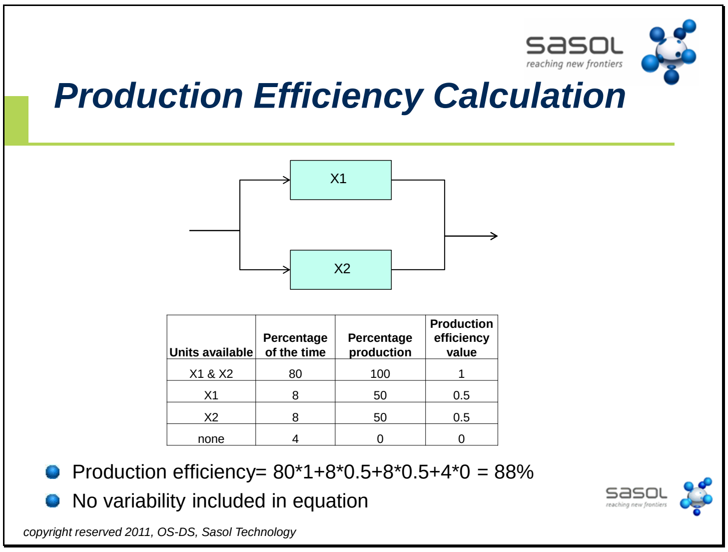
- A few things to remember:
  - *The RAM modeller and Stochastic Simulation Modeller's data need to be aligned at all times.*
  - *Validation of ones data and model needs to be done frequently*
  - *The Stochastic Simulation Modeller will need to do a few runs to test the RAM Modeller's data in other words, is the failures realistic.*
  - *RAM Modelling focus more on detail*
  - *Stochastic Simulation focus at throughput/volume, not so much at the detail*



RAM Plant availability calculation – example

Units available	Percentage of the time	Plant available	Availability value
X1 & X2	80	yes	1
X1	8	yes	1
X2	8	yes	1
none	4	no	0

- Plant availability = 80*1+8*1+8*1+4*0 = 96%
- Rule: one unit available – system available



Production Efficiency Calculation

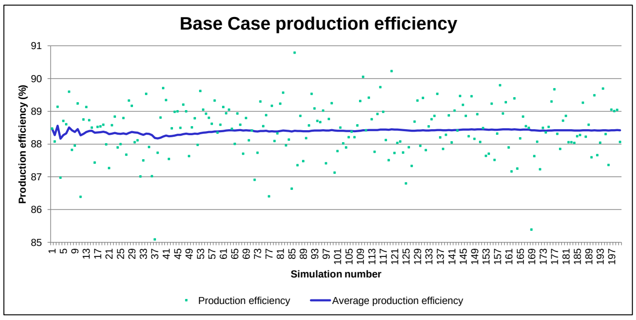
Units available	Percentage of the time	Percentage production	Production efficiency value
X1 & X2	80	100	1
X1	8	50	0.5
X2	8	50	0.5
none	4	0	0

- Production efficiency= 80*1+8*0.5+8*0.5+4*0 = 88%
- No variability included in equation

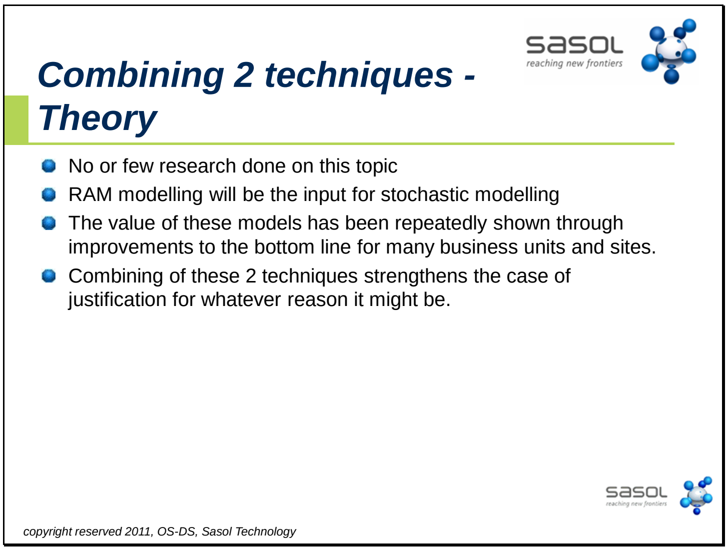
Base case scenario results - Main scenario

	Simulation production efficiency	Delta
Only breakdowns	94.21%	
Plus Shutdowns	90.04%	4.17%
Plus ramp up	89.93%	0.11%
Plus tanks	88.41%	1.52%

Base case simulation

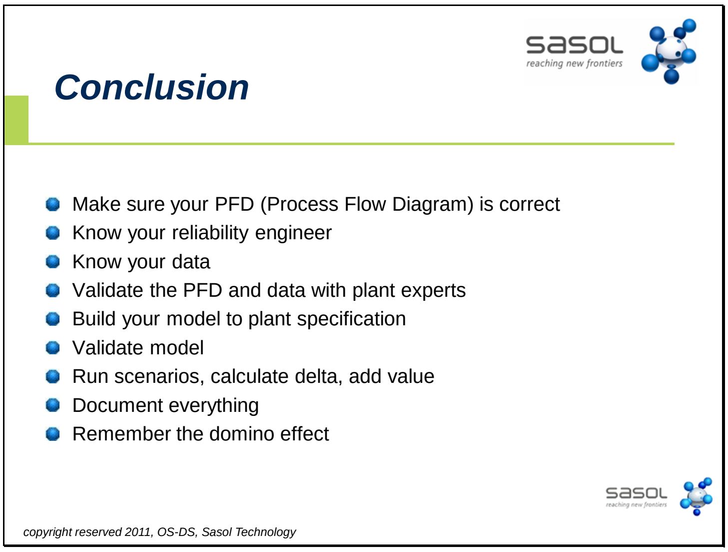

Base Case production efficiency

Variation = 5.71%



Combining 2 techniques - Theory

- No or few research done on this topic
- RAM modelling will be the input for stochastic modelling
- The value of these models has been repeatedly shown through improvements to the bottom line for many business units and sites.
- Combining of these 2 techniques strengthens the case of justification for whatever reason it might be.



Conclusion

- Make sure your PFD (Process Flow Diagram) is correct
- Know your reliability engineer
- Know your data
- Validate the PFD and data with plant experts
- Build your model to plant specification
- Validate model
- Run scenarios, calculate delta, add value
- Document everything
- Remember the domino effect