Reliability, Availability and Maintainability (RAM) Analysis for the Evaluation of Process Facilities

Plant reliability has become a key economic consideration for operating plants, as well as those new plants in concept development or in early design. Owners of operating plants use reliability modeling as a tool to identify availability bottlenecks, maintenance requirements, and sparing levels. Plants in the design phase use reliability modeling to verify a new design (frequently in conjunction with a conventional process design analysis) and to test the limits of a design in availability terms, before equipment commitments are made.

Reliability, availability, and maintainability (RAM) analyses utilize system engineering and discrete event simulation techniques to predict the characteristics of a production, process, or manufacturing facility. Equipment and event data is input into simulation software, which then generates statistical distribution of availability results using a Monte Carlo simulation engine. RAM analysis results provide owners with reasonable statistical bases for business decisions by defining a facility’s total performance over the facility life. Typical RAM results define the probability of achieving desired Availability or production targets, and provide criticality rankings of events which contribute to overall process losses.

This paper discusses the above methodologies using actual case studies of reliability analysis either for operating plants or new plant designs. As economics of ammonia plants, both older and new plants designs, become more competitive, the authors deem the above tools to be important more than ever.

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Introduction

Asset reliability and capacity capability are very important factors in the decision making process for evaluating the cost effectiveness of conceptual and existing operating plants. Reliability, Availability, and Maintainability (RAM) simulation analysis is a tool which incorporates reliability engineering techniques and systems engineering concepts (using Monte Carlo simulation software) to predict the future probabilistic behavior of a production, process, or manufacturing facility.

An effective, detailed RAM study will reduce investment cost, optimize maintenance & operations strategies, and educate operating and maintenance personnel in the functional capabilities of an operating facility.

The RAM analysis utilizes quantitative data to evaluate a facility’s design, operability, or functional issues that may impact the asset’s abilities to deliver the
desired product. A RAM simulation study utilizes the following factors:

- Equipment configuration and redundancies
- Equipment reliability (failure and repair characteristics)
- Facility operating strategy and characteristics
- Maintenance strategy and logistics

RAM simulation analysis is currently used in all process industries and is now required by some financial institutions to quantify investment risk.

KBR has extensive experience in developing and utilizing RAM simulation studies to determine optimum plant design, operation, and maintainability. This paper discusses the RAM simulation study approach, provides an Ammonia Plant case study, and KBR’s previous successes.

The RAM Modeling Process

RAM simulation techniques have become popular during the past several years in the process industry. This popularity is mainly due to increased cost effectiveness derived from an increase in computing power available to perform RAM simulations. Complex RAM analysis requires many computations and comparisons. Before the complexity of RAM simulation analysis is discussed the reader must understand the basic terms utilized in reliability engineering.

Reliability, availability, and maintainability are defined as follows:

Reliability. The probability of a system or component performing without failure for a specified function under a given condition for a specified period of time. The mathematical units utilized to describe this term are Mean Time Between Failure (MTBF) or Mean Time to Failure (MTTF).

Availability. The proportion of time that a system or component is capable of performing its duty. The equation for this ratio is – Operating Time (Total Online Time – Downtime) / Total Time (Typically a calendar year).

Maintainability. The measure of the ability of a system or component to be repaired or restored to specified condition when maintenance is performed by personnel having specific skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair. The mathematical units utilized to describe this term are Mean Time To Restore (MTTR) or Mean Time To Repair (MTTR).

To achieve effective results from a RAM simulation analysis it is essential to define the scope and boundaries for the deliverables of the desired results. This includes the level of detail at which the study will be performed, which equipment and systems will be part of the study, and what outside influences will be considered in the study. (i.e., utility & power supply reliability, sophistication of local personnel, business production interruptions, etc…)

The typical basis of a RAM analysis is the Process Flow Drawing (PFD) and, when available, the Piping and Instrument Diagram (P&ID). The PFDs and the P&IDs are utilized to provide the basic system configuration, hierarchy, and equipment redundancies of the facility to be analyzed. When RAM studies are performed in the early stages of project definition, finalization of the PFDs and P&IDs are part of the output of the study.

Often RAM simulation analyses are confused with Process simulation analyses, which examine flows, temperatures, pressures etc. for the technical capabilities of a facility. It is very important to understand that the RAM simulation analysis examines functionality and system/component interdependencies and should not be confused with a process simulation.

The Reliability Block Diagram (RBD) is the tool for mapping the reliability system configuration, hierarchy, and equipment redundancies of a facility. Utilizing a PFD and P & ID a Reliability Block Diagram is constructed to graphically indicate a system, subsystem, or component functionality to achieve a desired operating result. The RBD does not always indicate the actual physical connection of the facility. The structure of the RBD is determined by the system logic for achieving the required performance and does not always follow the process flow layout. Figure 1 illustrates a generic pump configuration in a 3 x 50% capacity arrangement.

Figure 1. Generic RBD 3 x 50% Capacity Pumps.
The structural blocks of the RBD which represent systems or components must be populated with reliability data. The data which indicates the failure frequency component is Mean Time Between Failure (MTBF) or Mean Time To Failure (MTTF). The fundamental component of MTBF and MTTF is failure rate. Failure Rate is defined as:

\[ \lambda = \text{Number of Failures per Unit of Time} \]

\[ \text{MTBF or MTTF} = \frac{1}{\lambda} \]

MTBF is the failure terminology for repairable systems and MTTF is the failure terminology for non-repairable systems. Since the majority of system or component failures of an operating facility are repairable, MTBF will be utilized to describe the failure properties of the RBD for an operating facility. The other data point needed to populate the RBD blocks is duration of the system or component outage which is expressed as MTTR.

The final piece of information needed for the RAM analysis is to assign a probability distribution function (pdf) to each failure and repair data point. Exponential probability distributions are commonly utilized for repairable systems. The exponential distribution is associated with the ability to repair failed systems or components to “as good as new” condition therefore, an existing system or component has just as much opportunity to fail as a repaired system or component. This failure mode is referred to as the constant failure rate of the Bathtub failure rate curve. (See figure 2). Other probability distributions are normal, log-normal, and weibull.

The general assumptions for development of the RBD structure and failure data are incorporated in reliability simulation software to analyze the behavior of the facility through time. There are several RAM modeling programs that are commercially available such as MAROS, SPAR, and Witness 2001 developed by Jardine Associates, Clockwork and Lanner respectively. Most software programs utilize Monte Carlo simulation engines. A Monte Carlo simulation engine uses a random sampling technique to determine when an event occurs and its duration. The simulation generates samples from the probability distribution of the failure and repair data. The simulation is run for many lifecycles. A life cycle is a scenario of system performance over time. For example if a facility was simulated for 20 years and 100 lifecycles, the software examines 20,000 (20 years x 100) random responses of the facility performance over time. Typical outputs of the simulation are production availability probability of risk curves, ranking of systems or components that causes production unavailability, evaluation of system or component sparing, and more depending upon the software of choice. Figure 3 summarizes the RAM simulation study process.

![Bathtub Curve](image)

**Figure 2. Bathtub Curve.**
Ammonia Plant Case Study

The case study for this paper highlights the Carbon Dioxide Removal unit of an Ammonia plant located in China. The CO₂ removal system utilizes an activated amine process. The deliverables for the RAM study are 1) the production availability for the process and 2) failure ranking of the systems which contributed to downtime for the process.
Failure data for this study consist of typical mechanical and instrumentation related failures, and, operational upsets experienced in locations where experienced ammonia plant operators are not readily available.

The PFD is converted into a RBD for the system configuration, equipment redundancies, and functional interactions of the system. The RBDs for the Carbon Dioxide Removal unit are illustrated in figures 5, 6, 7, 8.

Figure 4. CO2 Removal Process Flow Diagram.

Figure 5. Carbon Dioxide Removal System Overview.
Figure 6. Carbon Dioxide Removal Rich Solution.

Figure 7. Carbon Dioxide Removal Lean Solution.
The RBDs for this case study were populated with failure and repair data and simulated for 20 years and 200 lifecycles. Figure 9 is the production availability analysis for the Carbon Dioxide Recovery Unit.

The production availability risk S-curve indicates a 90% probability (P90 value) that the facility will operate at an average of 98.6% of the total production capability. The (P50) value indicates a 50% probability of an average 99% production capability. This is based on a 20-year life of the asset.

The bars indicate the frequency at which a given production availability value is developed by the simulation.

The RAM simulation is also capable of ranking the equipment which have caused production unavailability as illustrated in Figure 10.

The summary of this Case study for the Carbon Dioxide Removal unit indicates expectant production availability of 98.94%. The overall absolute loses are 1.06% with the major contributor being the CO2 Absorber, which impacts the absolute losses by approximately 21.49%. In this model, the absorber suffers multiple modes of failure. The most significant with regards to production impact, is a foaming/carry-over event in which the solution is carried downstream past the knock-out drum to impact the methanator catalyst.
Figure 10. Carbon Dioxide Removal Criticality Rankings.

<table>
<thead>
<tr>
<th>Description</th>
<th>Relative Losses</th>
<th>Absolute Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 Absorber</td>
<td>21.49</td>
<td>0.23</td>
</tr>
<tr>
<td>CO2 Stripper</td>
<td>15.98</td>
<td>0.17</td>
</tr>
<tr>
<td>Stripper Reboiler/LTS Syn</td>
<td>15.05</td>
<td>0.16</td>
</tr>
<tr>
<td>Stripper Bottoms Cooler</td>
<td>12.04</td>
<td>0.13</td>
</tr>
<tr>
<td>Stripper Bottoms Recovery</td>
<td>7.48</td>
<td>0.08</td>
</tr>
<tr>
<td>LTS Syngas/BFW Exchanger</td>
<td>7.40</td>
<td>0.08</td>
</tr>
<tr>
<td>CO2 Stripper Overhead cooler</td>
<td>6.66</td>
<td>0.07</td>
</tr>
<tr>
<td>Absorber Knock-Out Drum</td>
<td>3.60</td>
<td>0.04</td>
</tr>
<tr>
<td>Wash water Knock-Out Drum</td>
<td>3.44</td>
<td>0.04</td>
</tr>
<tr>
<td>High Pressure Flash Drum</td>
<td>3.41</td>
<td>0.04</td>
</tr>
<tr>
<td>Processed Syngas Knock-Out</td>
<td>3.35</td>
<td>0.04</td>
</tr>
<tr>
<td>Hydraulic Recovery Turbine</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
<td><strong>1.06</strong></td>
</tr>
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</table>

Figure 11. System Criticality Rating.

Note: Typically, major rotating equipment is on the list of high impact items, but in this case, all the rotating equipment in this unit is spared or may be bypassed. In units or facilities where large compressors, pumps, or turbines are critical to the operation and are not spared, it is not unusual to see those equipment items as major contributors to system un-availability.

This chart represents the impact of the critical CO2 plant systems. The relative loss indicated the percentage of the total losses or absolute losses the unit experiences.

KBR Experience

KBR began using Reliability analysis in the early 1990’s, prompted by client and lender’s requests for performance data in addition to the process design requirements typically given by technology providers. As Reliability technology and computer applications improved, the use of RAM analysis became more widespread, with more chemical and petrochemical clients using RAM analysis in addition to the upstream / offshore oil & gas industry. By the late 1990’s RAM became another tool for predicting the behavior of operating facilities, in use by global operators and NOCs (National Oil Companies) as well as government and military installations.

In the late 1990’s as a result of corporate acquisitions and mergers, KBR developed its own capability for RAM modeling, using industry standard software. The ability to develop and use these models in house
has greatly increased both our understanding of the technology and our ability to effectively apply RAM analysis to all phases of capital projects.

KBR currently uses RAM analysis as part of the Process Reliability Modeling Value Improving Practice (VIP) workshop for capital projects. Process Reliability Modeling is one of several industry best practice activities recommended by Independent Project Analysts (IPA) for execution early in the life of a project. This and other VIPs have yielded improved project efficiency and reduced overall project costs when performed at the correct time with involvement by client and contractor personnel.

In addition to formal VIPs, RAM analysis can be used on projects to assist the project team in identifying opportunities for increased availability or production, or to reduce the overall cost of a facility to the owner over the life of the facility. RAM modeling is typically used in one of three ways:

- On grass-roots projects as a tool for predicting total production availability and annual product quantities prior to detailed design. The RAM model results are used to optimize equipment configuration, assist with operating cost estimates and to allow selection of equipment at the lowest overall cost to the client over the life of the facility.
- On upgrade and revamp projects, RAM is a tool for maximizing plant availability and minimizing operating costs by assisting owners to make informed decisions on design changes, sparing philosophies and maintenance practices.
- Through analysis of existing plant designs, maintenance data, sparing levels, and overall facility availability, Reliability modeling provides the existing plant-site with specific recommendations for increasing overall availability, optimization of resources, and cost reduction.

Reliability engineers work with project personnel, Operations and Maintenance advisors, client personnel, and industry or vendor data bases to develop a project specific reliability model of a facility. The Reliability model is then used to generate sensitivity analyses for each proposed plant modification or equipment configuration to yield the highest availability/lowest cost choices for the project.

Figure 12 on the next page lists some of the RAM models KBR has performed recently.

Project Summaries

Following are summaries of two reliability studies done on existing facilities, and one study done for a new facility. Each of these projects used formal RAM modeling early in the design phase to assist the project with decisions on capital equipment.

Project 1

A reliability study was conducted for a 3-train LNG facility in the Middle East. The intent of the study was to quantify the current total facility performance and identify improvements, resulting from implementation of specific debottlenecking activities. The scope of the reliability study included the upstream offshore wellheads and production platforms, onshore receiving facilities, three LNG trains and all supporting utility services. The boundaries of the model extended to the LNG tanker, the condensate storage tanks and the sulfur storage tanks. The model included systems and equipment whose failure would adversely affect LNG production.

The reliability model contained over 3000 equipment items, each with an average of two unscheduled failure modes. Main planned shutdown activities were included to provide realistic representation of the actual facility performance.

Preliminary results predict the ‘base case’ total facility availability at around 92%, including planned shutdown events. The study validated the proposed debottlenecked design basis, and also identified several areas of potential improvement not associated with capital equipment. Equipment and systems responsible for significant failure events and cumulative total failures were identified for further review by the client maintenance organization.

Project 2

KBR performed a RAM study on an Ethylene upgrade project. The major objective of this study was to quantify reliability and availability improvements associated with the installation of new equipment.
The methodology employed for this project included the modeling of the existing ethylene unit as a Base case against which subsequent expansion cases were compared. The Base case was developed utilizing data mined from the site, supplemented as necessary by industry reliability data. Once the proper feed slate data was input into the model and the simulation was run, the predicted production efficiency (availability stated in the quantity of product produced) was within 1% of the actual production experience of the plant averaged over the past 10 years. This was deemed adequate for project requirements and the Base case model was considered validated. The Base case was then utilized as a template for upgrade case models, with equipment being removed, added, and/or modified in the subsequent models as requested by the project team. In all, over 35 iterations of the Base case model were developed.

The study was performed at a “major equipment” level of detail. Utilities were modeled at 100% (or no impact) and certain “one of a kind” catastrophes were not included in the model or the reliability data. Maintenance response times were unchanged between models. It was decided that a conservative approach would be used when assigning reliability improvements to existing equipment to be modified during the project. This study was successful in describing the anticipated improvements in plant reliability as a result of the upgrade design. It also identified areas where further studies could be performed that would have the most impact on the total plant production efficiency. The validation of the RAM methodology gained by the accurate prediction of existing plant availability through the development of the Base Case was essential for credible development and comparison with the Upgrade Models.

One of the cases tested using the reliability model was the feasibility of increasing the duration between planned turnarounds from 5 to 8 years. Using performance data from the existing plant and projected maintenance and repair data, the model predicted that 7 years was the optimal interval between turnarounds. Plant availability and consequent production started to decline in year 7, contributing to production losses in ex-

<table>
<thead>
<tr>
<th>Activity Description</th>
<th>Client</th>
<th>Type of Facility</th>
<th>Status</th>
<th>Date</th>
<th>Scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAM analysis</td>
<td>Qatargas</td>
<td>LNG</td>
<td>Complete</td>
<td>Sep-99</td>
<td>Model existing facility and establish plant availability and production capacity of 20 year life-cycle as part of facility Debottlenecking study.</td>
</tr>
<tr>
<td>RAM analysis</td>
<td>BP/Amoco</td>
<td>TMA</td>
<td>Complete</td>
<td>Jun-00</td>
<td>Model new facility and develop analysis for different equipment configurations.</td>
</tr>
<tr>
<td>RAM Analysis</td>
<td>Confidential</td>
<td>Power Generation</td>
<td>Complete</td>
<td>Oct-00</td>
<td>Pre-funding assessment of overall facility availability, including comparisons of 3 design cases.</td>
</tr>
<tr>
<td>RAM analysis</td>
<td>BP/Amoco</td>
<td>TMA</td>
<td>Complete</td>
<td>Jul-00</td>
<td>Model existing facility and simulate proposed changes for upcoming expansion project.</td>
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<tr>
<td>RAM analysis</td>
<td>BP/Amoco</td>
<td>Ethylene</td>
<td>Phase 1 complete</td>
<td>May-01</td>
<td>Model existing facility and simulate proposed changes for upcoming expansion project.</td>
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<td>RAM analysis</td>
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<td>LNG</td>
<td>Complete</td>
<td>Sep-02</td>
<td>Model new facility and develop analysis for different equipment configurations.</td>
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<td>RAM analysis</td>
<td>BP</td>
<td>LNG</td>
<td>Phase 1 complete</td>
<td>Oct-02</td>
<td>Model new facility and develop analysis for different equipment configurations.</td>
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<td>RAM analysis</td>
<td>Petrobras</td>
<td>Oil &amp; Gas</td>
<td>ongoing</td>
<td>Jun-03</td>
<td>Model new offshore facility and develop analysis for different equipment configurations relative to production risks.</td>
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<td>RAM analysis &amp; plant audit</td>
<td>KNPC</td>
<td>LPG</td>
<td>ongoing</td>
<td>Jun-03</td>
<td>Model existing facility and establish plant availability and plant improvement study.</td>
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<td>Model existing facility and establish plant availability and plant improvement study.</td>
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<td>RAM analysis</td>
<td>SHELL</td>
<td>Refinery</td>
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<td>Provide RAM data and modeling for furnace upgrade</td>
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<tr>
<td>RAM &amp; RCM analysis</td>
<td>SASOL</td>
<td>Proprietary</td>
<td>ongoing</td>
<td>Jun-03</td>
<td>Model new onshore facility and develop analysis for different equipment configurations in proprietary design. Provide RCM analysis for critical equipment items.</td>
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</table>

Figure 12. KBR Recent Experience.
cess of the production gained by stretching the TAR interval to 8 years. Using the reliability model data to recommend a 7-year turnaround interval prevented potential failures and lost production in year seven, which more than compensates for the cost of the study.

Project 3

A reliability study was conducted for a confidential gas-to-power project as part of a pre-funding due diligence effort. The basis for development of a reliability model was to test the inter-dependencies between units and the effect of individual and collective unit dependencies (and risks) on the overall availability of the facility. The facility was modeled as a single train plant, with no spared equipment.

The reliability study included sufficient planned and unplanned failure data to analyze the influence of subsystem design and performance uncertainties on overall performance, and on the intermediate performance of each subsystem. Further, for those subsystems containing downtime data for individual equipment items, the results pointed to specific equipment items and systems where the inclusion of critical spares may result in a significant increase in overall production.

The results obtained for this pre-engineering study were sufficient for input into the client’s commercial model, and showed a level of facility and component availability required for the due diligence effort. Further, more detailed comparisons incorporating additional equipment and component data were recommended for the front-end engineering phase to maximize overall plant availability with minimum capital and operating investment.

Conclusions

In conclusion, RAM simulation analysis is a powerful tool for predicting future behavior of an asset, identifying the systems and equipment contributing most to lost production, and predicting the availability impact of future revamps, or upgrades. The power of the RAM model is that with little effort, design scenarios composed of different equipment configurations and/or maintenance organizations may be compared quickly with results measured in impact to the overall plant production efficiency. When used in conjunction with RCM tools and production planning, RAM tools can also be used to optimize operating, maintenance, and sparring strategies for long term facility management.

Bibliography