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DYNAMIC POSITIONING CONFERENCE

October 12-13, 1999

RELIABILITY SESSION

Assessing The Reliability Of Dynamic Positioning Systems For Deepwater Drilling Vessels

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ASSESSING THE RELIABILITY OF DYNAMIC POSITIONING SYSTEMS FOR DEEPWATER DRILLING VESSELS

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Abstract

Since the late 1970's dynamic positioning has become a well-established means for maintaining vessel location and heading by use of active thrust. The acceptance and growth in number of vessels using DP has grown steadily in offshore oil and gas and other industries. DP systems are built to different levels of redundancy (or ability to withstand component failure). The function of this redundancy is to allow for safe operation after part of the DP capability of the vessel has been lost due to either a hardware or a software failure. When designing such systems, questions that may arise include:

- *What single point failures exist?*
- *How reliable are the system components?*
- *Is the system's desired level of redundancy met?*
- *How is system reliability factored into the decision making process?*

The importance of answering these questions is real. Recent incidents in the deepwater drilling industry have shown that the cost implications of unreliability are severe. System downtime may put the rig/vessel out of service for hours, days or months or even lead to confidence problems and cancellation of contract. The losses are directly drawn from the bottom line. Majors in the drilling industry have expressed a need for tools and techniques to assist in selecting a cost-effective design alternative with high reliability and safety potential.

This paper describes some well-established tools for addressing common design questions related to risk and reliability. Furthermore, the paper discusses how cost implications of system unreliability can be incorporated into cost/benefit analyses and business decision analyses that seek to select a system with lowest total life cycle cost.

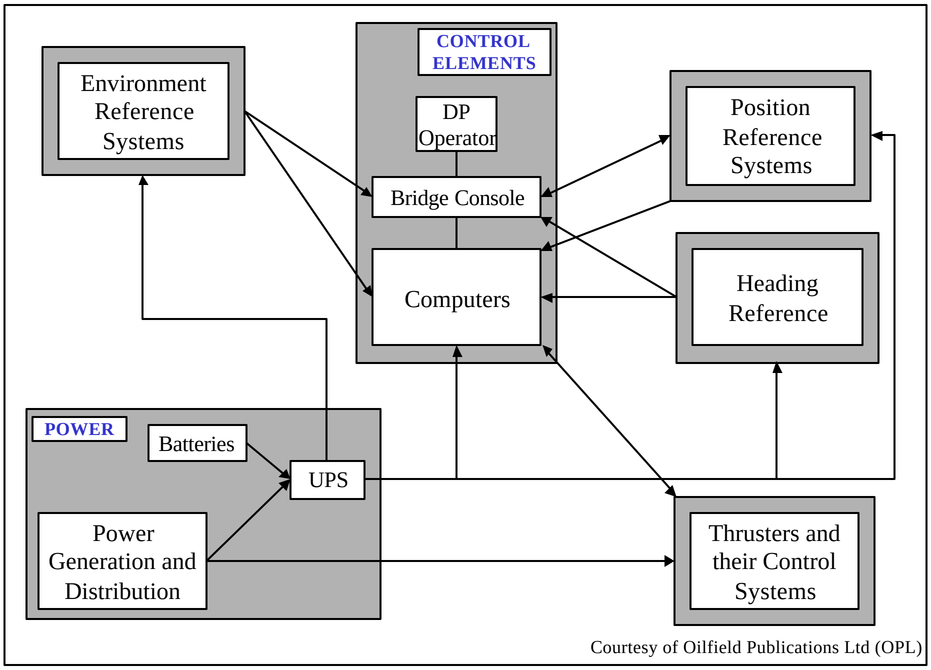
I. INTRODUCTION

The use of Dynamic Positioning (DP) has become a well-established means for maintaining vessel position and heading by use of active thrust. The acceptance and growth in number of vessels using DP has grown steadily with over 400 in use as of a year or two ago. DP vessels are now involved in almost all types of vessel functions including the following:

- Exploration and Production Drilling
- Pipelay (rigid and flexible pipe)
- FPSO (floating production, storage, and offloading vessels)
- Multi-role support vessels
- Subsea installations
- Well stimulation and workover

One definition of dynamic positioning is *a system which automatically controls a vessel to maintain her position and heading exclusively by means of active thrust* /1/. A DP system contains many different subsystems that vary greatly (computers, thrusters, sensors, etc.), but are brought together to provide the capability to maintain a vessel position and heading. A general schematic of a typical DP system is provided below in Figure 1.

Figure 1: General Schematic of a Typical DP System



The need for DP vessels to maintain position and heading is critical for most offshore deepwater applications. Identified worst case events on DP vessels are often associated with the loss of station keeping either through drift off or drive off scenarios. These worst case events highlight the need for a highly reliable DP system that a vessel operator can trust. Even the perception that a DP system is unreliable may cause unnecessary delays and cost overruns. Understanding of what can go wrong, how likely are they, and what are the consequences, i.e. understanding the risks, is crucial during the design and operation of the vessel.

II. RECENT EXPERIENCES

Recent experiences involving DP vessels illustrate the criticality of DP systems. In the past few years, DP vessels have experienced incidents ranging from delays in operation through brown out and up to rig blackout. Examples include:

- Significant corrosion problems with power transformers for thruster motors due to air and seawater ingress.
- Inadvertent closure of a fuel return valve resulting in a rig blackout.
- All generator governor controls sent through a single electronics card resulting in a rig blackout.

Fortunately none of the above events resulted in a catastrophic incident due to protective systems in place, prompt personnel response, or luck that a critical operation was not being performed at that time.

Severe consequences resulting from the loss of station keeping include the potential to damage the subsea stack or wellhead during drilling operations, damage to pipelines during a pipelay operation, collisions, etc. These consequences can result in high costs to projects, as well as extended downtimes and project overruns. Long term consequences may even result in loss of confidence with the DP vessel operator and eventual loss of contract. Due to the severity of a DP failure, a great deal of emphasis has been put on improving the reliability of the DP systems.

III. DP CLASSIFICATION

The industry currently measures DP reliability through a general class system. The major classification societies (DNV, ABS, Lloyds, etc.) base their DP classification on the guidelines set down by the International Maritime Organization (IMO) with only minor modifications. A synopsis form these guidelines are given below /2/. Equipment classes are define by their worst case failure modes as follows:

- "For equipment class 1, loss of position may occur in the event of a single fault"
- "For equipment class 2, a loss of position is not to occur in the event of a single fault in any active component or system. Normally static components will not be considered to fail where adequate protection from damage is demonstrated, and reliability is to the satisfaction of the Administration. Single failure criteria includes:
    - *Any active component or system (generator, thrusters, switchboards, remote controlled valves, etc.).*
    - *Any normally static component (cables, pipes, manual valves, etc.) which is not properly documented with respect to protection and reliability.*
- "For equipment class 3, single failure criteria includes:
    - *Items listed above for class 2, and any normally static component is assumed to fail.*
    - *All components in any one watertight compartment, from fire or flooding.*
    - *All components in any one fire sub-division, from fire or flooding…"*
- "For equipment classes 2 and 3, a single inadvertent act should be considered as a single fault if such an act is reasonably probable."

The three IMO classes correspond to three increasing levels of redundancy for DP vessels. In order to qualify a DP system at the higher class levels, the operator must demonstrate that the DP system is not vulnerable to a single point failure from an active component (class 2) or a single point failure from any active or static component, including fire or flood in one compartment (class 3). Therefore the identification and elimination of single point failures is an integral part of the design of a DP system.

Identification of single point failures and determination of the levels of redundancy that are available within a DP system are often found through the use a Failure Mode and Effects Analysis (FMEA). This type of study is usually a specified requirement of any DP vessel before the vessel is given a class 2 or 3 equivalent classification.

IV. RELIABILITY AND AVAILABILITY ASSESSMENT

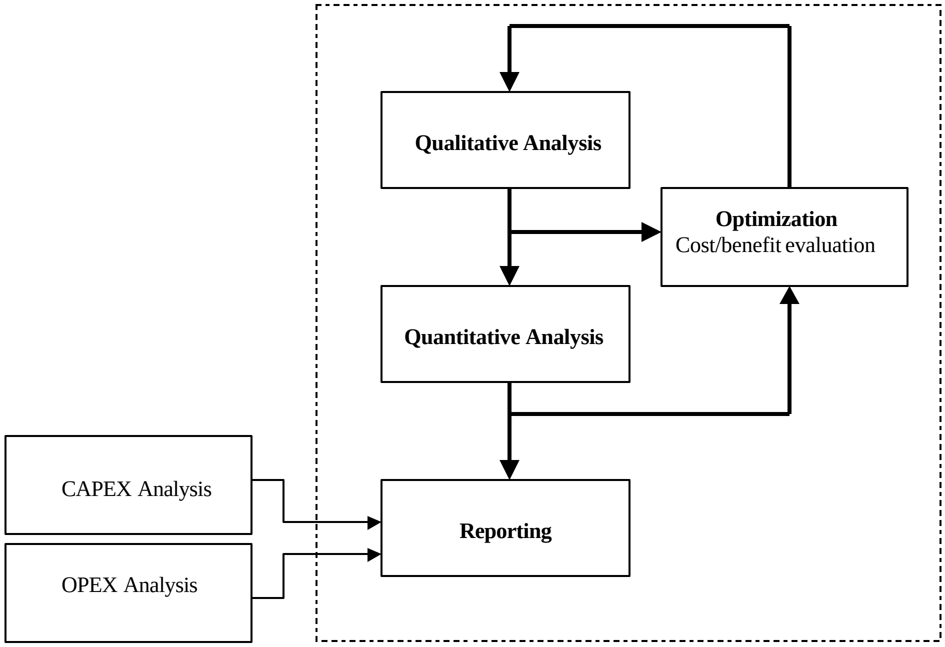
There are several analysis techniques that can be used to assess the reliability and availability of DP systems. These techniques are normally divided into two categories:

- Qualitative analysis
- Quantitative analysis

The work process of a typical reliability assessment is illustrated in Figure 2. The qualitative analysis is normally carried out by using a technique called Failure Mode and Effects Analysis (FMEA) /3,4/. Other techniques are available, but the FMEA is the most frequently used.

An FMEA for a DP system can be performed to varying levels of detail depending on the type of questions that need to be answered and on the state of the design. In order to prioritize the results of the study, a criticality ranking is often performed on the identified failures/events in tandem to the FMEA. The criticality ranking is performed by grouping the consequence and associated frequency of each of the failures to establish a risk picture. The results from the ranking exercise identify a risk level for that event. This modified study is termed a Failure Mode, Effects, and Criticality Analysis (FMECA).

Figure 2: Reliability Assessment – Work Process



An FMECA is extremely useful to identify single point failures, identify critical operating issues and to develop a priority driven approach to addressing possible improvements. A natural progression following the initial FMECA is to study the different systems or subsystems of concern in a more quantitative detail. Key parameters such as the frequency of drive off, the frequency of drift off and fraction of time with trouble free operation over a specified period of time can be predicted using quantitative techniques, e.g. Reliability Block Diagram Analysis (RBDA) and Fault Tree Analysis (FTA). In addition, quantitative techniques can be used to identify ways to improve system reliability. If the cost associated with the improvements is lower than the value of the increased uptime, the improvements will increase the overall system performance and profitability. Therefore, the quantitative reliability models can be used to *optimize* the DP system from a cost/benefit point of view by assigning a cost to the improvements and comparing that to the value of the increased uptime. The more detailed models allow the analyst to focus in on critical areas of the DP design to ensure that the overall design is as reliable as practical.

The FMEA technique is described in more detail in Section V while some quantitative techniques are described in Section VI.

System reliability and availability has an influence on all major aspects of total system performance such as:

- Value of system uptime (trouble-free time, safety)
- Operating expenditures (OPEX)
- Capital expenditures (CAPEX)

Designs improving reliability and maintainability will increase system uptime, e.g. the fraction of trouble-free time and the fraction of time with safe performance. Likewise, designs improving reliability and maintainability reduces OPEX because of less failures and shorter time periods for which repair resources are required. CAPEX include the costs of initial design, engineering & construction and investments related to modifications during the vessel lifetime. Whether built-in availability increases or decreases the CAPEX is not as important as whether the investment is beneficial from a reliability and safety point of view.

When considering up-front investments, reliability and safety considerations offer the following advantages:

1. Cost savings can be achieved by avoiding attention to areas that are non-critical and improving areas where the cost/benefit are highest. For instance, availability considerations can be used to justify the investment in increased functional redundancy as well as individual equipment with higher reliability and maintainability.
2. Reliability and availability considerations normally lead to discovery of enhancement opportunities during the conceptual and design phase rather than later in the project's life where the cost of change is much higher. Furthermore, enhancements made in later phases of the vessels life may have been preceded by foregone income opportunities.

V. FAILURE MODE AND EFFECTS ANALYSIS

Failure mode and effects analysis (FMEA) /3,4/ was one of the first systematic techniques for failure analysis. It was developed by reliability engineers in the late 1950s to study problems that might arise from malfunctions of military systems.

A failure mode and effects analysis is often the first step of a system reliability assessment. It involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes, causes, and effects of such failures. For each component the failure modes and their effects on the rest of the system are documented on a specific FMEA worksheet.

An FMEA becomes a failure mode, effects, and criticality analysis (FMECA) if criticalities or priorities are assigned to the failure mode effects.

V.1 Benefits of an FMEA

A failure mode and effects analysis (FMEA) is mainly a qualitative analysis, and is typically carried out by the designers during the design stage of a system. The purpose is to identify single point failures where improvements are needed to meet reliability requirements such as DP2 or 3 classification. An FMEA is therefore an important basis for design reviews.

The benefits of an FMEA are multifold. Benefits include:

1. Assistance in selecting design alternatives with high reliability and high safety potential during early design phase.
2. Assurance that all conceivable failure modes and their effects on operational success of the system have been considered.
3. Generation of a list of potential failures along with assessment of the magnitude of their effects.
4. Basis for establishing corrective action priorities.
5. Objective evaluation of design requirements related to redundancy, failure detection systems, fail-safe characteristics, and automatic and manual override.
6. Development of early criteria for test planning and the design of the test and checkout systems.
7. Assistance in developing operating procedures and trouble-shooting guidelines.
8. Provides historical documentation for future reference to aid in the analysis of field failures and consideration of design changes.
9. Provides a basis for quantitative reliability and availability analyses, and subsequent cost/benefit studies.

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V.2 Analysis Approach

The failure mode and effect analysis can be carried out either by starting at the component level and expanding upward (the bottom-up approach), or from the system level downward (the top-down approach). The bottom-up approach is often referred to as the *hardware approach*, while the top-down approach is referred to as the *functional approach*.

It is a general rule to expand the analysis down to a level at which there is a good understanding of the failure mechanisms, the failure rates and the failure impacts. However, it is often necessary to make compromises regarding the detail to which the analysis should be conducted, since the workload could be overwhelming even for a system of moderate size if the detail of the approach is taken to an individual part level.

The basic questions to be answered by an FMEA are:

1. How can each part/component/sub-system (depending on level of detail) conceivably fail?
2. What mechanisms might produce these modes of failure?
3. What could the effects be if the failures did occur?
4. Is the failure in the safe or unsafe direction?
5. How is the failure detected?
6. What inherent provisions are provided in the design to compensate for the failure?

A failure mode and effects analysis is a systematic design review, which is relatively simple to conduct. It does not require any specialized analytical skills from the personnel performing the analysis. It is, however, necessary to know and understand the system that is analyzed and the constraints under which it operates.

VI. QUANTITATIVE TECHNIQUES FOR RELIABILITY ASSESSMENT

A commonly used term within the arena of reliability assessment is RAM (Reliability, Availability and Maintainability). The RAM analysis considers three important aspects of system performance:

- Reliability expresses as the *likelihood of surviving a certain time period* under given operating conditions.
- Maintainability expressed as *the time to return failed or shutdown equipment back to normal service*. Influencing factors are working conditions, organization of work, procedures, and resources.
- Availability expressed as *the percentage of time the equipment is able to perform its intended function* under given operating conditions. Availability is a function of reliability and maintainability.

VI.1 The Basic Formula for Availability

Reliability is a probability distribution of the time to failure. When calculating the availability, the mean value in the probability distribution is used. Likewise, maintainability is a probability distribution. It is a probability distribution of the time to restore the equipment back to normal service. When calculating the availability, the mean value in the probability distribution is used. Maintainability includes the expectation that maintenance tasks and their support requirements fall within a pre-defined range. The availability is mathematically defined as:

$$A = \frac{R}{R + M}$$

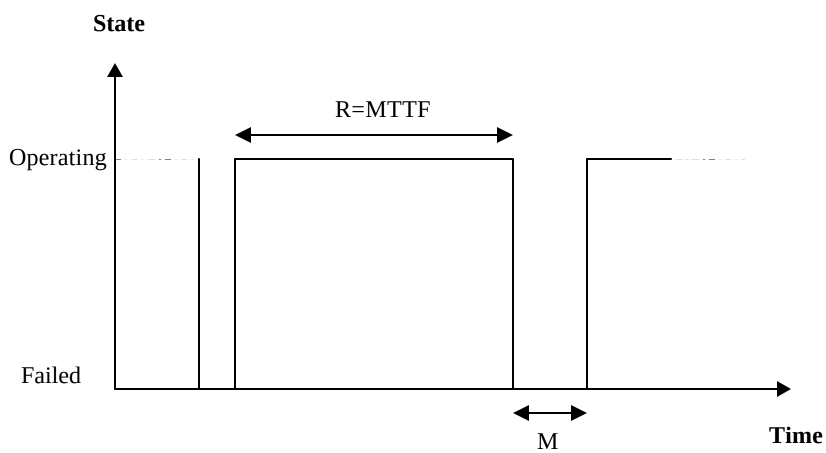
Where: **R** = Reliability expressed as Mean Time To Failure (MTTF).

A = Availability.

M = Maintainability expressed as the mean time to return failed item to service.

The availability can be increased by increasing the mean time to failure or reducing the time to return failed items to service. However, the costs of improving reliability and maintainability can outweigh the benefits if the cost associated with the improvements is higher than the value of the increased uptime and safety. A visual interpretation of the formula above is given in Figure 3.

Figure 3: Illustration of The Basic Formula for Availability



For instance, if a dual redundant Programmable Logic Controller (PLC) has a mean time to failure (MTTF) of 120 000 hours (~13.7 year), and a mean repair time (M) of 5 hours, the availability is 120,000/[120,000 +5] = 0.99996 = 99.996%, which corresponds to approximately 20 minutes of downtime per year on average.

The term availability can have several meanings depending on the types of maintenance activities incorporated in the assessment. To illustrate this, consider the two different interpretations of availability:

- Achievable Availability (A_A): This measures the availability when corrective and preventive maintenance are considered without including associated logistic and administrative time, i.e. active repair time only. This assumes a perfect maintenance support environment.
- Operational Availability (A_O): This includes corrective and preventive maintenance including associated logistic and administrative time, i.e. time for troubleshooting, acquiring and delivering of maintenance resources, active repair time, testing and start-up. This measure reflects the operation's resource levels and organizational effectiveness. Together these two measures isolate the effectiveness and efficiency of maintenance operations. Achievable availability reflects equipment reliability, equipment redundancy and configuration and built-in-design maintainability.

VI.2 Quantitative Techniques

There are several analysis techniques /3,4/ that can be used as a basis for RAM analysis. The most common techniques are:

- Reliability Block Diagram (RBD)
- Fault Tree (FT)
- Network Simulation (NS)
- Markov Chain Model (MCM)

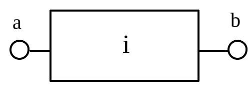
These techniques are briefly described in the following sub-sections.

Reliability Block Diagram

A reliability block diagram (RBD) analysis is a deductive (top-down) method. A RBD is the graphical representation of a system's logical structure in terms of sub-systems and components. The RBD allows the system success paths to be represented by the way in which the sub-systems and components are logically connected. A RBD is appropriate to model one system function only. If the system has more than one function, each function is considered individually, and a separate RBD is necessary. The output from a FME(C)A can be used as input for the RBD. Whereas the FME(C)A is well suited for a system with little or no redundancy, systems with complex redundancies can be analyzed with RBDs.

Consider a system with *n* different components. Each of the *n* components is illustrated by a block as shown in Figure 4.

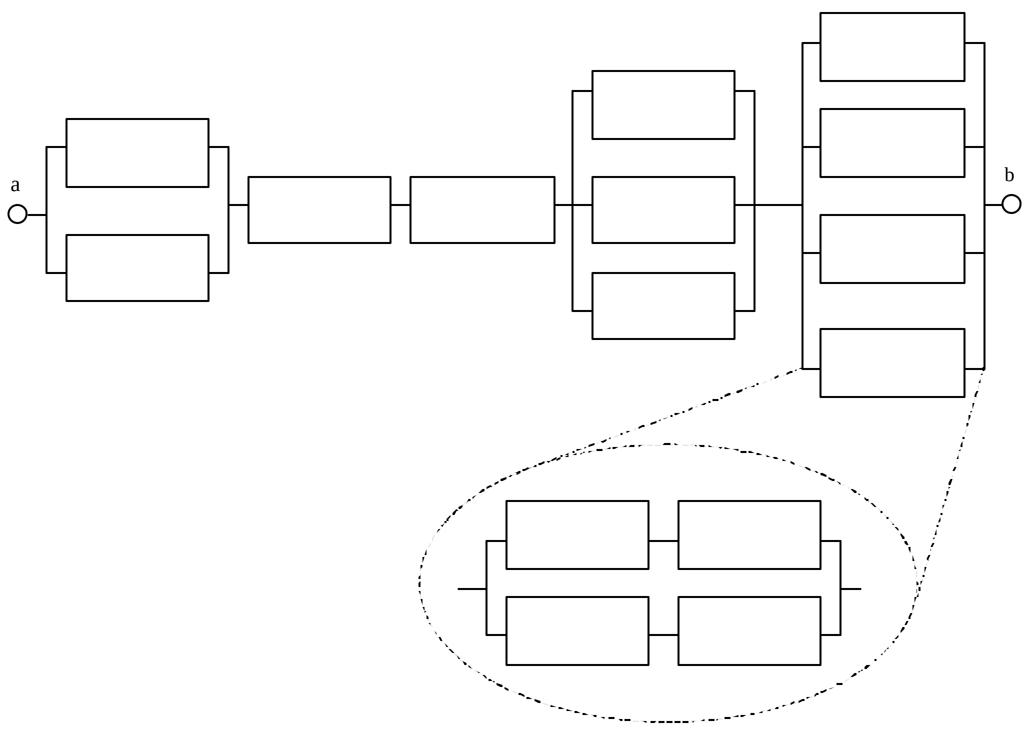
Figure 4: Component *i* Illustrated by a Block



When there is connection between the end points (*a*) and (*b*) as in Figure 4 component *i* is considered functioning as designed. This does not necessarily mean that component *i* functions in all respects. It only means that one, or a specified set of functions, is achieved (i.e., that some specified failure mode(s) do not occur). What functioning means must be specified in each case and will depend on the objectives of a particular study.

The way the *n* components are interconnected to fulfill a specified system function may be illustrated by a reliability block diagram, as shown in Figure 5. The specific system function is considered achieved, when there is a connection between the end points (*a*) and (*b*) in Figure 5, which means that some specified system failure mode(s) do(es) not occur.

Figure 5: System Function Illustrated by a Reliability Block Diagram



It should be emphasized that a reliability block diagram is not a physical layout diagram for the system. It is a logic diagram, illustrating one function of the system.

Fault Tree

Fault tree analysis (FTA) is a means of analyzing system failures in terms of *combinations* of subsystem and lower level faults, and eventually component faults. Because the FTA is a top-down approach it is possible to start the analysis at a very early stage and to complete it as the detailed design is carried out. A fault tree illustrates the states of the system's components (basic events) and the connections between these basic events and the system's state (Top Event). The graphical symbols used to represent these connections are called logic gates. The output from a logic gate is determined by the input events.

The FTA can be carried out as a qualitative or quantitative analysis. The FTA will produce a list of possible serious component fault combinations, including any single point failures. The probability of the top event and hence system reliability or availability can be assessed. The output from an FME(C)A can be used as input for the FTA. Whereas the FME(C)A is well suited for a system with little or no redundancy, systems with complex redundancies can be analyzed with FTA.

Network simulation

Network simulations normally apply the Monte-Carlo simulation technique. A Monte Carlo (stochastic) simulation is carried out by generating discrete events in a computer model (sampled from relevant probability distributions) in order to create a realistic or "typical" lifetime scenario of the system components. The state of all the components is computed in the same way.

The situation is then reviewed to determine the overall state of the system. If failures have occurred, there may be various changes in the system, such as initiation of repair of failed critical components. A realization of the system life is simulated and, after having observed the simulated system for some time, estimates of the desired measures of performance are made, such as average lost production volume, average repair cost and mean number of failures per time unit. Thus, the simulation is treated as series of real experiments.

Network simulations are suitable for the evaluation of functionally complex structures, redundant configurations, complex repair and maintenance strategies, time limited bypass operations, component dependencies and limitation in the access to repair resources.

Markov Chain Model

Markov analysis is mainly an inductive (bottom-up) analysis method suitable for the evaluation of functionally complex structures and complex repair and maintenance strategies. The method is based on the theory of Markov chains. In principle the probabilities of system elements (components, equipment, sub-systems) being in a particular state at specific points (or intervals) of time are evaluated by mathematical models.

The qualitative analysis requires the determination of all the possible system states, preferably shown diagrammatically in a state-transition diagram. The transition probabilities and the way in which the states are related, represented by the state-transition diagram, allow the construction of the desired transition matrix (mathematical model) for the purpose of system reliability/availability calculations.

Software Tools

Examples of software packages that can be used to facilitate the calculations for the various techniques are listed in Table 1.

Table 1: Software Tools for Quantitative Reliability Assessment

TECHNIQUE	SOFTWARE TOOL
Reliability Block Diagram	WinRAMA
Fault Tree	CARA
Network Simulation	MIRIAM, EXTEND
Markov Chain Model	EXTEND, MATLAB, SYSTAT

VI.3 Reliability Data

Data selection is a difficult task since, in many cases, the main purpose of the reliability assessment is to facilitate the qualification process of new technology (no historical track record). It is therefore difficult to find experience data with high confidence and tolerance. Confidence, the statistical measurement of uncertainty, expresses how well the measured parameter through experience data represents the actual parameter. Confidence in the data increases as the sample size is increased. Tolerance uncertainty arises from the physical, the operating and the environmental differences among members of differing equipment samples when failure data are aggregated to produce a final generic set. Increasing the number of sources used to obtain the final data set will most likely increase the tolerance uncertainty.

However, in most cases it is possible to find reliability data on similar components even though the system and the application area could be slightly different. In fact this is one of the strengths of the system reliability techniques mentioned earlier where statistical methods are used to aggregate component data up to equipment, sub-system and finally system level.

In situations where limited data are available, the following approaches /3/ have led to successful results:

- Ranking Techniques
- Expert Judgements
- Bayesian Techniques

VI.4 Performance Parameters

Different measures can be used to evaluate the performance of the analysis object. Which parameter(s) to chose depends on the questions that should be answered. System availability is the most frequently used measure. Other typical performance measures are:

- Mean time between system failures.
- Mean system downtime per failure.
- Frequency of occurrence for critical failure modes.
- Average number of hours with lost function per year.
- Probability that the system will function on demand.
- Probability of surviving a specified time period under given conditions.
- Maintenance resource utilization per time period.
- Number of maintenance resource mobilizations per time period.

When availability is predicted, importance measures can be defined by the contribution to system unavailability from each item/event. An approach frequently used to deal with this issue is successive sensitivity analyses where the contribution from each item, activity or event is set to zero.

VI.5 Identification of Possible Improvements

The structure of a RAM analysis makes it easy to identify the items/failure modes that have greatest effect on the availability. This together with an uncertainty assessment should form the basis for identifying availability improving measures. These measures will include the elements where the expected improvement is greatest, but will not state whether it is cost effective to implement the measure. The expected increase in availability has to be seen in context with the possible increased CAPEX and OPEX associated with the availability improving measure.

VII. APPLICATION OF RELAIBILITY ASSESSMENT

As described in the previous sections, there are several established techniques for addressing common design questions related to reliability. Each technique has some advantages and some disadvantages. Table 2 gives a summary of the differences between a failure mode and effects analysis (FMEA) and a reliability, availability and maintainability (RAM) analysis in terms of study input/output, resource requirements and advantages/disadvantages. This table can be used to select the study approach that will give the best support for a particular decision making process.

Table 2: Reliability Assessment In Brief

	Typical Inputs/Outputs	Resource Requirements	Advantages	Disadvantages
FMEA	Studies are typically conducted using system schematics, PFDs and/or P&IDs. Output consists of tables of text that document the system components, how they fail, and the impact of their failure.	Study facilitator (knowledgeable in the FMEA process) and area experts who have a detailed understanding of system components, system operation, failure mechanisms, and local and global effects of the failures.	Systematic review of the system design. Identification of single point failures. Study does not require any special tools to complete. The FMEA process is relatively simple.	Studies can be time consuming if assessment taken to a part level. Cost/benefit can not be directly calculated from an FMEA.
RAM	Studies are typically conducted using system schematics, PFDs and/or P&IDs. Failure frequency databases. Financial information for cost/benefit calculations. Numerical output detailing system performance in terms of mean time to failure (MTTF), mean time to repair (MTTR) and system availability. Cost/benefit analysis can produce figures which detail the cost of a modification and the cost savings associated with the modification in terms of enhanced availability or reduced expenditures.	Analysts familiar with reliability techniques along with software to facilitate the numerical processing (calculations and simulations). Analysts must have an understanding of system failures (typically the results of an FMEA) and the associated repair requirements.	Powerful optimization tool during design. Quantifies key system performance parameters, and identifies ways to improve system performance. Allows for optimization of the system from a cost/benefit point of view. Since models are typically built using specialty software, sensitivity analyses are easily carried out.	Normally more time consuming than an FMEA. Modeling requires failure frequency databases that are often proprietary to either manufactures or companies that provide reliability analysis services.

VIII. CONCLUSIONS

DP systems offer advantages over traditional mooring systems in certain applications. Based on the positive performance track record to date, they are only going to grow in number and application. A failure within the state-of-the-art active thrust positioning system can however have serious consequences. A number of codes, standards, rules and regulations have been developed to help ensure that the design of DP systems meets a minimum standard. Unfortunately the development of technology outpaces the rate at which these standards documents are generated. Furthermore, economic pressures and competition force companies into adopting and including technology advancements as fast as they surface. So, are we left to just learning by experience?

Fortunately, the answer is no. The challenges posed by early adoption of new technology are not unique to the oil and gas industry. Tools such as FMEA and RAM can be used to proactively identify shortcomings that may have otherwise gone unnoticed. Furthermore, these tools offer excellent opportunities for design optimization with respect to lifecycle costs. FMEA studies allow for early discovery of single point failures that could have resulted in a system trip, loss of redundancy or worse yet a system failure. Class Societies require FMEA studies since, if done properly, they offer excellent proof that the system under consideration has been reviewed thoroughly. FMEA studies are also the first logical step in carrying out quantitative reliability studies. Quantitative reliability studies allow for cost-benefit techniques to be used during system optimization. Since so much is at stake with these modern DP applications (asset value and cost of an accident or unplanned shutdown) often designers are confronted with making “million dollar” decisions. Through quantification and factual understanding of the costs of a design change and benefit of the change, sound economic decisions can be made.

Reliability studies can be time consuming and costly. However, the direct cost savings and/or the increased revenues achieved through carrying out these studies have been estimated to fall between a factor of 10-15 over their cost.

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