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Reliability Centered Maintenance

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Forward

This document on Reliability Centered Maintenance is prepared for Norsk Forening for Vedlikehold (NFV). Per Schjølberg has been responsible for the report. The work has been carried out by Johan O. Asmundvaag, Per Schjølberg and Peter Okoh.

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Contents

Tables

Figures

1. Introduction

Reliability centered maintenance (RCM) is a conceptual approach to maintenance analysis methods that originated from the airline industry in the late 1960s as a tool for preventing failures with significant consequences, such that Reliability, Availability, Maintainability and Safety under the acronym "RAMS elements" are balanced. In the 1960's the airline industry suffered with an unacceptable incident and accident rate primarily caused by technical failures. The technology had moved from slow, propelled aircrafts to high speed, jet driven, cabin pressurized aircrafts and the traditional experience-based maintenance philosophy could not control the failure mechanisms sufficiently. It is borne from the consideration that the traditional maintenance methods would improve safety and affect return on investment since aircrafts would be too costly to maintain. RCM has developed over the years and has come to stay as an optimal maintenance solution if applied to the right situation in the right way. Currently, the application of RCM cuts across diverse industries.

Aims and Objectives

This report intends to present RCM in both theoretical and practical contexts. The objective is to create a better insight for both hands-on and administrative maintenance personnel.

Limitations

- The traditional RCM is extended in this report.
- This report is generic and not tailored to any particular industry.

Working Methods

The work is based on literature review, personal industrial experience and opinions from seasoned industrial experts.

Report Structure

In the beginning, the book will define Reliability Centered Maintenance (RCM). It will later present the goals, benefits, the 7 basic RCM questions and the RCM analysis process. Furthermore, it will shed light on Risk Based Reliability Centered Maintenance (RBCM), a form of RCM. Finally, it will discuss the need to integrate RCM and Computerized Maintenance Management System (CMMS).

Acronyms

Some abbreviations used in this document are given below. Others are defined where used:

ARP	-	Age Replacement Policy
BS	-	British Standard
CBM	-	Condition Based Maintenance
CMMS	-	Computerized Maintenance Management System
CoF	-	Consequence of Failure
FFA	-	Functional Failure Analysis

FMECA	-	Failure Modes, Effects and Criticality Analysis
H	-	High
HSE	-	Health, Safety and Environment
HSE-UK	-	Health and Safety Executive, UK
IEC	-	International Electrotechnical Committee
ISO	-	International Standards Organization
L	-	Low
KPI	-	Key Performance Indicators
M	-	Medium
MIL	-	Military
MTBF	-	Mean Time Between Failures
MTTF	-	Mean Time To Failure
NOK	-	Norwegian Kroner
NORSOK	-	A Norwegian standard
OREDA	-	Offshore Reliability Data
PF	-	**P**otential failure – **F**unctional failure interval
PFD	-	Probability of Failure on Demand
PM	-	Preventive Maintenance
PoF	-	Probability of Failure
RAMS	-	Reliability, Availability, Maintainability and Safety
RBI	-	Risk Based Inspection
RBM	-	Risk Based Maintenance
RBCM	-	Risk Based Reliability Centred Maintenance
RCM	-	Reliability Centred Maintenance
RPN	-	Risk Priority Number
SAE	-	Society of Automotive Engineers
SCE	-	Safety Critical Element
TBM	-	Time Based Maintenance
VL	-	Very Low
WCM	-	World Class Maintenance

2. Reliability Centered Maintenance (RCM)

Reliability Centered Maintenance (RCM) is a maintenance analysis method that systematically assigns appropriate preventive maintenance tasks to items at optimal frequencies in order to retain their ability to perform their required functions over a given period of time.

On a standard basis, IEC 60300-3-11 (IEC, 2010) defines RCM as a "systematic approach for identifying effective and efficient preventive maintenance tasks for items in accordance with a specific set of procedures and for establishing intervals between maintenance tasks."

RCM is widely recognized by maintenance professionals as the most cost-effective way to develop world-class maintenance (WCM) strategies. RCM generally leads to a prioritization of maintenance tasks based on some indices that indicate equipment characteristics and importance.

2.2 Goals of RCM

The main goals of an RCM analysis are:

1. To identify critical and non-critical functions and limit the amount of analysis work **(Functional Failure Analysis, FFA)**
2. To identify maintenance tasks that can sustain equipment reliability **(Task analysis)**.
3. To evaluate the cost-effectiveness of the maintenance tasks **(Cost-Benefit analysis)**.
4. To establish a plan for the application of the selected maintenance tasks at an optimal interval **(Reliability improvement)**.

2.3 Benefits of RCM

RCM leads to speedy, substantial and sustained improvements in:

- Plant/production availability
- Equipment reliability
- Product quality
- Safety integrity
- Environmental integrity
- Return On Investment

2.3 The Seven Fundamental Questions of RCM Process

According to the SAE JA1011 (SAE, 1999), the minimum criteria that any RCM process must fulfill in order to be a true RCM process, is to be able to answer the following seven questions:

1. What are the functions and associated desired standards of asset in its present operating context? **(Functional requirements?)**
2. In what ways can it fail to fulfill its functions? **(Functional failures/Failure modes?)**
3. What causes each functional failure? **(Failure causes?)**
4. What happens when each failure occurs? **(Failure effects?)**

5. In what way does each failure matter? **(Failure consequences?)**
6. What should be done to predict or prevent each failure? **(Proactive tasks and task intervals?)**
7. What should be done if a suitable proactive task cannot be found? **(Default actions?)**

2.4 RCM Analysis Process

A number of variations exist in the application of RCM today. The following is an RCM approach that satisfies the stipulations of SAE JA1011.

1. Preparation for analysis
2. Functional failure analysis (FFA)
3. RAMS data collection
4. Failure modes, effects and criticality analysis (FMECA)
5. Maintenance task analysis (MTA)
6. Maintenance interval assessment (MIA)
7. Maintenance tasks comparison (MTC)
8. Computerized Maintenance Management System (CMMS) database updating

Step 1: Preparation for Analysis

This involves preliminary work done preparatory to the actual RCM analysis process. This involves the following:

- **Technical review:** A cross-functional team including system engineers, maintenance and operation representatives and an RCM expert reviews relevant policies, guidelines and standards.
- **System selection:** Screening of systems is carried out based on the consequence level of a functional failure and system complexity to limit the extent of the analysis and to eliminate unnecessary analysis work. Relevant RAMS information should be obtained about the actual system or similar system. RCM analysis takes time and resources; so, an unwise application (i.e. on every piece of equipment) will lead to cost overruns rather than savings. Hence, it is advisable to perform it (by FFA) only on selected equipment or levels of assembly (plant, system, subsystem) that will yield dividends from it.
- **System boundaries or scope definition:** Specification of limits of application in terms of levels of technical assembly, whether at plant, system or subsystem level. The level for the functional failure analysis (FFA) should be at a manageable level meaning a functional level where a functional failure has direct impact to the RAMS elements. The technical assembly level for the maintenance task analysis (MTA) should be at a LRU level (Line Replaceable Unit).
- **Collection of documentations and manuals:** Retrieval of all technical materials relevant to the system under consideration, including assembly drawings, design datasheet and operational manuals.

Step 2: Functional Failure Analysis (FFA)

This step involves the following sub-steps:

- **Identifying system functions:** Classification of functions (essential, auxiliary, protective, information, interface, superfluous, online or offline) and analyzing whether they are significant or not. The task of column 1 (listing of relevant functions) of the FFA worksheet shown in Table 2 could be made easier, but more conservative, by applying the function selection decision tree shown in Figure 1.

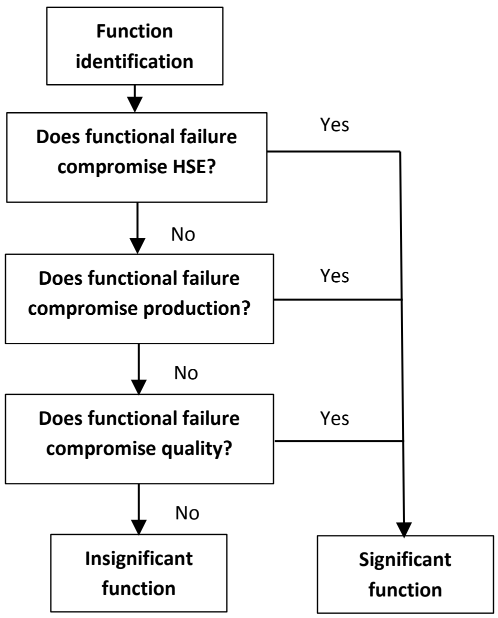

Figure 1: Significant function selection logic tree, adapted from **(NAVAIR 00-25-403, 2005)**

- **Identifying potential functional failures (i.e. failure modes):** Complete failure to perform a function, under-performance of a function, over-performance of a function or performance of an unintended function.
- **Identifying functional failure consequences for every operational mode:** This aims to set a threshold for further analysis by eliminating insignificant functional failures. The functional failure in column 4 of the FFA worksheet in Table 2 should be considered significant, if the consequence falls within the category range A to F in the proposed consequence rating shown in Table 1:

Table 1: Consequence rating applied in Functional Failure Analysis (FFA) (Okoh, 2010)

Consequence	**Description**
Consequence **A**	Functional failure of equipment compromises HSE (HSE-critical) without redundancy.
Consequence **B**	Functional failure of equipment does not compromise HSE, but stops production (Production-critical) without redundancy.
Consequence **C**	Functional failure of equipment does not compromise HSE and does not stop production, but reduces quality (quality-critical) without redundancy.
Consequence **D**	Functional failure of equipment has no effects on HSE and production and quality, but cost of maintenance is above, for e.g., NOK10K (Maintenance-critical) without redundancy.
Consequence **E**	Functional failure of equipment is HSE-critical/production-critical/quality-critical/maintenance-critical and full redundancy exists.
Consequence **F**	Functional failure of equipment is HSE-critical/production-critical/quality-critical/maintenance-critical and partial redundancy exists.
Consequence **G**	Functional failure of equipment has no effects on HSE and production and quality, but cost of maintenance is below, for e.g., NOK10K (mostly run to failure)

If the consequence does not fall within the range A to F of Table 1, the equipment should be omitted from further maintenance task analysis but should be considered regarding corrective maintenance cost which is dependent on spares/repair cost and the failure frequency of the equipment. If single cost is below above criteria, but failure frequencies are considered significant, the equipment should be included in the FMECA to decide if further analysis has any utility value.

Table 2: Functional Failure Analysis (FFA) worksheet adapted from (Okoh, 2010)

System: *Performed by:*
Ref. Drawing No: *Date:* *Page: of:*

				Consequence rating							
Function	Opera-tional mode	Function require-ments	Functional Failure	A	B	C	D	E	F	G	Significance confirmation

Each of the columns in Table 2 can be explained as follows: The column “Function” is filled by significant systems functions (e.g. to regulate fluid flow) based on the output of the function decision tree described in Figure 1. The column “Operational mode” describes the way(s) in which the desired function is recognized (e.g. opening/closing of valve) in operation. The column “Function requirements” describes criteria (e.g. open/close within 5 seconds) that ensure function fulfillment. The column “Functional failure” describes the way(s) in which the desired function can be considered unrealized (e.g. too early/late actions). The column “Consequence rating” is as described in Table 1. The column “Significance confirmation” presents a final verdict about the significance status of the function. Based on the decision in this column, further relevant information associated with the prioritized functions are collected as explained further in step 3. To a large extent, the FFA serves as an input to the FMECA worksheet in Table 3.

Step 3: RAMS Data Collection

This involves the gathering of RAMS data for further qualitative and quantitative analysis. The qualitative analysis may cover relevant failure modes and failure causes, while the quantitative analysis may encompass reliability quantities such as MTTF, ageing parameter, PF intervals etc.

Step 4: Failure Modes, Effects and Criticality Analysis (FMECA)

According to (MIL-STD-1629A, 1980), *Failure Mode and Effects Analysis (FMEA)* is "a procedure by which each potential failure mode in a system is analyzed to determine the results or effects thereof on the system and to classify each potential failure mode according to its severity" while *Criticality Analysis (CA)* is "a procedure by which each potential failure mode is ranked according to the combined influence of severity and probability of occurrence." *Failure Mode, Effects and Criticality Analysis (FMECA)* is hence the combination of *FMEA* and *Criticality Analysis* (MIL-STD-1629A, 1980).

An FMECA worksheet, intended to serve as a source of information for the RCM logic and maintenance interval optimization to be treated later, is shown in Table 3.

Table 3: FMECA Worksheet (Okoh, 2010)

System: *Performed by:*
Ref. Drawing No: *Date:* *Page: of:*

Description of units			Description of failure			Failure Effect		Failure Rate	Repair Rate	Aging	Criticality				Risk Reduc-ing Measure
Ref No.	Func-tion	Opera-tional mode	Failure Mode	Failure Cause	Detection of failure	On sub-system	On system function				HSE	Prodtn Volume	Qual-ity	Maint Cost	

A recommendation by (SAE JA1012, 2002), advises that "failure modes should be described in enough detail for it to be possible to select an appropriate failure management policy, but not in so much detail that excessive amounts of time are wasted on the analysis process itself."

Criticality Terminologies

Criticality: Criticality is synonymous with the risk associated with the event of equipment failure, where risk, according to (ISO 17776, 2000) is "combination of probability of an event and the consequence of the event." Criticality, according to the military standard, is defined as "a relative measure of the consequences of a failure mode and its frequency of occurrences" (MIL-STD-1629A, 1980).

Criticality Analysis: Criticality Analysis, according to the British standard, is "a quantitative analysis of events and faults and the ranking of these in order of the seriousness of their consequences" (BS 3811, 1993). Criticality analysis, according to the military standard, is "a procedure by which each potential failure mode is ranked according to the combined influence of severity and probability of occurrence" (MIL-STD-1629A, 1980).

Criticality Assessment: Criticality Assessment, according to (Healy, 2006) "is a structured methodology that provides a proactive approach for the assessment of risks in the organization."

Critical Equipment: Critical Equipment, as defined by (Smith & Mobley, 2007) "is that equipment whose failure has the highest potential impact on the business goals of the company."

Safety-critical systems: They are systems that have the potential to pose a serious risk to the safe operation of the whole facility, *e.g.,* (1) structural integrity systems, (2) ignition control systems, (3) process containment systems, (4) fire, smoke, gas detection systems, (5) fire protection systems, (6) shutdown systems, (7) blowdown and relief systems, (8) emergency response systems, (9) lifesaving systems, (10) blast walls, (11) Heating, Ventilation and Air Conditioning (HVAC) systems, (12) Communication systems and (13) blow-out prevention systems (HSE, 2009). For the listed safety-critical systems, recognized and accepted by Health & Safety Executive (HSE) UK, it is not necessary to do, *for e.g.*, an RCM, RBI or FMECA to determine whether the system is critical or not.

Production-critical equipment: They are equipment that have the potential to cause loss of production time or reduction in production availability, *e.g.,* separators, pumps, turbine, compressors etc.

Quality-*critical systems:* They are systems in which certain deviations would lead to non-conformance to specifications - a quality issue that may become tied to loss of reputation, legislative implications or legal actions. Such systems may be software systems integrated with all types of computer systems used in manufacturing such as, Programmable Logic Controllers (PLCs), Personal Computers (PCs), Process Computers and networked systems (Margetts, 1991). The systems may be involved in the control of variables in continuous processes, batch processes or materials handling operations (Margetts, 1991).

Risk Priority Number (RPN) and Risk Matrix

The RPN or risk matrix may be used to provide the input for the criticality column in the FMECA worksheet shown in Table 3.

Criticality analysis may be used to prioritize risks by virtue of *Risk Priority Number (RPN)*. The *RPN* is the product of detectability (D), severity (S) and occurrence (O). Each quantity is usually based on a scale of 1 to 10. Hence, the highest *RPN* of 1000 (i.e. 10 x 10 x 10) means that the failure is not detectable by inspection, very severe and the occurrence is almost certain. If the occurrence is very unlikely, then O = 1 and the *RPN* would be reduced to 100. In summary, the aim of the analysis here is to reduce the RPN as much as possible for a safer operation. If RPN is considered, the FMECA table may be modified as shown in Table 4:

Table 4: FMECA Worksheet with RPN

System: *Performed by:*
Ref. Drawing No: *Date:* *Page: of:*

Description of units			Description of failure			Failure Effect		Failure Rate	Repair Rate	Aging	Criticality					Risk Reduc-ing Measure
Ref No.	Func-tion	Opera-tional mode	Failure Mode	Failure Cause	Detection of failure	On sub-system	On system function				D	S	O	RPN	Comment	

Alternatively, Criticality analysis may enable prioritization of risks with the aid of a risk matrix. The risk matrix charts the frequency/probability of the failure mode against the consequences of the failure as shown in Table 5.

Table 5: Risk matrix used for classification and decisions, adapted from (Okoh, 2010)

RISK MATRIX USED FOR CLASSIFICATION AND DECISION

Severity	Consequences				Frequencies				
	HSE	Produc-tion Volume	Quality	Mainte-nance Cost	1 Very Unlikely	2 Remote	3 Occasio-nal	4 Probab-le	5 Freque-nt
5	Disastr-ous Impact	Disastr-ous Impact	Disastr-ous Impact	Disastr-ous Impact	M	H	H	H	H
4	Critical Impact	Critical Impact	Critical Impact	Critical Impact	L	M	M	H	H
3	Major Impact	Major Impact	Major Impact	Major Impact	L	L	M	M	H
2	Minor Impact	Minor Impact	Minor Impact	Minor Impact	L	L	L	M	M
1	Slight Impact	Slight Impact	Slight Impact	Slight Impact	L	L	L	L	L
0	No Impact	No Impact	No Impact	No Impact	VL	VL	VL	VL	VL

Severity	Consequences				Frequencies				
	HSE	Produc-tion Volume	Quality	Mainte-nance Cost	1 Very Unlikely	2 Remote	3 Occasio-nal	4 Probab-le	5 Freque-nt
5	Disastr-ous Impact	Disastr-ous Impact	Disastr-ous Impact	Disastr-ous Impact	5	10	15	20	25
4	Critical Impact	Critical Impact	Critical Impact	Critical Impact	4	8	12	16	20
3	Major Impact	Major Impact	Major Impact	Major Impact	3	6	9	12	15
2	Minor Impact	Minor Impact	Minor Impact	Minor Impact	2	4	6	8	10
1	Slight Impact	Slight Impact	Slight Impact	Slight Impact	1	2	3	4	5
0	No Impact	No Impact	No Impact	No Impact	0	0	0	0	0

The risk scale (very low-VL, low-L, medium-M and high-H) or the corresponding color coding (green, blue, yellow and red) implicitly establishes risk acceptance criteria. The consequences should have specified values and are described as an example in Table 6.

Table 6: Risk matrix consequence classes description (Okoh, 2010)

Consequence	Description
Disastrous impact	Impact that leads to more than 3 fatalities/continuous extreme environmental degradation that will lead to economic loss over a wide area/sudden and total loss of production/extreme quality reduction in large quantity of products/maintenance cost in excess of 10 million NOKs.
Critical impact	Impact that leads to permanent total disability, or 1 to 3 fatalities/extreme environmental degradation that will require extensive measures for remediation/up to two weeks shutdown/substantial quality reduction in large quantity of products/maintenance cost between1 to 10 million NOKs.
Major impact	Impact that leads to long-term disabilities or chronic health impairment /substantial environmental degradation that will persist and require clean-up/up to one week shutdown/substantial quality reduction in substantial quantity of products/maintenance cost between 100,000 to 1 million NOKs.
Minor impact	Impact that leads to lost work days up to 5 days/minor environmental degradation with transient effect/partial shutdown/minor quality reduction in products/maintenance cost between 10,000 and 100,000 NOKs.
Slight impact	Impact that leads to first aid cases and medical treatment cases /slight environmental degradation that is contained within immediate location/brief stops or disruptions/insignificant quality reduction in products/maintenance cost below 10,000 NOKs.
No impact	No injury or health impairment/ no environmental impact/ no production stop/no quality reduction/no maintenance cost

Step 5: Maintenance Task Analysis (MTA)

Appropriate task selection is a step towards realizing maintenance strategy optimization. Maintenance strategy optimization entails the application of the most cost-effective technique or method to a given maintenance program.

A guide to selecting appropriate task is the use of RCM decision logic into which significant failure modes and corresponding failure mechanisms (from a prior FMECA) are ideally fed, in order to decide between the suitability of a preventive maintenance task and an intentional operate-to-failure (OTF) for corrective maintenance. A RCM decision logic is shown in figure 2.

The RCM logic indicates the most appropriate maintenance tasks from among the following:

- Redundancy deployment *)
- Continuous condition monitoring
- Periodic condition monitoring
- Periodic repair
- Periodic replacement
- Periodic function test
- Operate to failure

*) Redundancy deployment is normally a design matter. For the RCM analysis redundant design is required if no maintenance task is effective to prevent failures in Critical equipment developing to an undesirable event. In other cases a cost benefit analysis may recommend a redundant design to reduce maintenance cost.

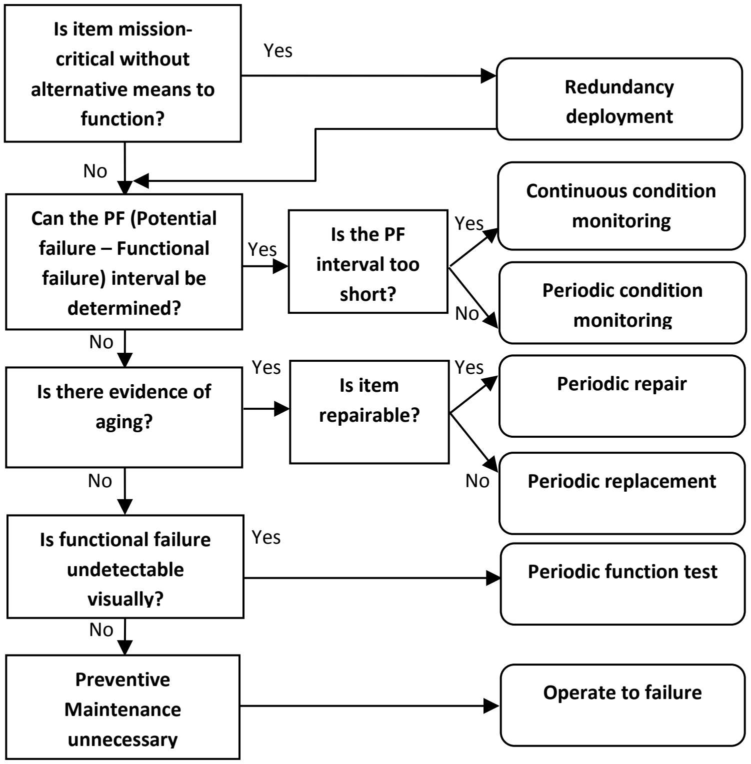

Figure 2: RCM decision logic, adapted from (Rausand & Vatn, 2008)

The PF interval, which forms part of the considerations in the RCM decision logic, refers to the duration between the detection of a potential failure and the subsequent functional failure as illustrated in Figure 3.

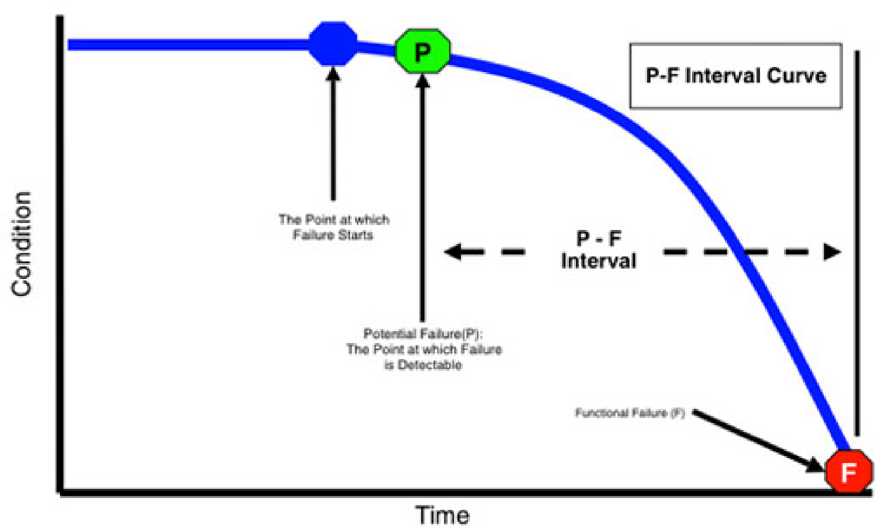

Figure 3: PF-interval curve (culled from http://zzeed.wordpress.com/2011/04/25/reliability-centered-maintenance-training/)

The knowledge of PF-Interval enables us to avoid unexpected failures, unplanned downtime and unnecessary holding cost incurred by keeping certain spares in stock. If the PF-Interval is enough for us to get a component to site, plan it and replace a defective one, then there is no need to hold it in the stores at all. But if you have a PF-Interval of, *for e.g*. three weeks and a spare delivery lead time of, *for e.g*. five weeks, then it would be wise to hold a spare in stock.

Note: *The knowledge of a P-F interval includes knowledge of the equipment's failure characteristics. The P-F interval cannot be determined on failure event statistics alone.*

Redundancy deployment: It is the installation of active shared-load or stand-by redundant system in a situation whereby an item is critical to the success of a mission and the mission when in progress cannot tolerate an interruption for any other form of maintenance. Such a system is such that the functional failure of a component must be instantly obviated by the systemic availability of another component while the mission continues. Mission-critical components are parts (equipment, process, procedure, software, etc.) of a system or an organization that are necessary for the success of the core function of an organization or system. The definition of degrees of redundancy could vary from one organization to another. An example of degrees of redundancy is shown in Table 7.

According to (NORSOK Standard Z-008 rev. 3, 2011), compensating operational actions used to temporarily maintain a function can be described as redundancy and used for priority of operational actions.

Table 7: Examples of degrees of redundancy (Okoh, 2010)

Redundancy Class	Redundancy Description
A	No redundancy i.e. the probability of loss of function is required to be very low in the system.
B	Partial redundancy i.e. there is possibility of partial fulfillment of function in event of system failure
C	Full redundancy i.e. there is possibility of full fulfillment of function in event of system failure

Continuous Condition Monitoring: It is the continuous inspection of an item to detect any potential failure. This task is applicable where the interval between potential failure and functional failure (PF interval) is too short. The task is also applicable where it is possible to measure certain variables for which certain observations are indicative of failure. It is also typical to have an integrated early-warning system.

Periodic Condition Monitoring: It is the scheduled inspection of an item to detect any potential failure. This task is applicable where the interval between potential failure and functional failure is (PF interval) is reasonable and determinable.

Periodic Repair: It is the scheduled repair of an item at or before some specified time in service or amount of duty (i.e. age limit) usually considered to be associated with rapid failure progression. This task is applicable whereby an item is repairable and such a repair can increase the remaining life of the item reasonably.

Periodic Replacement: It is the scheduled substitution of an item (or a part of an item) supposedly with another of higher integrity at or before some specified time in service or amount of duty (i.e. age limit) usually considered to be associated with rapid failure progression. This task is applicable where the item is irreparable or the cost of repair is uneconomical compared to the cost of item renewal.

Periodic Function Test: It is a scheduled inspection of an item where the functional state is passive and it is impracticable to detect a faulty state visually. Some safety critical systems are typical systems that justify the applicability of this task.

Operate to Failure: It is a deliberate decision to use an item without maintaining it until it fails either because it is unmaintainable or it is uneconomical to maintain it. Such items are usually non-critical.

Step 6: Maintenance Interval Assessment (MIA)

Maintenance interval assessment involves the determination of the most cost-effective frequency for the application of a maintenance strategy in a given maintenance program since both under-maintenance driving in-service failures and over-maintenance driving maintenance cost are undesirable. For new technical system design this is realizable with the aid of cost, component and system performance models, namely: Weibull PM model, ARP model, PF model, PFD model, etc. For technical systems proven in use or comparable with a reference systems, adequate maintenance and engineering experience may be used. Relevant operational, utilization and environmental conditions should be identified to compensate for determination of intervals.

Step 7: Maintenance Tasks Comparison (MTC)

Maintenance task comparison entails identifying differences between the selected task and the existing maintenance practice in order to analyze what features may be needed in a new maintenance programme and their effects on the system and organization.

Step 8: CMMS Database Updating

Record-keeping is an essential aspect of the RCM process. This will promote the effectiveness of maintenance programmes during an equipment life cycle. In the event of future reviews of the maintenance strategy (even by a new team), there may be consistence in effectiveness due to the availability of records of all decisions taken before and by whom and under whatever circumstances. In preparation of the analysis, performance indicators should be identified as an input to the operator’s Computerized Maintenance Management System (CMMS).

3. Risk Based Reliability Centered Maintenance (RBCM)

The benefits of an RCM is not experienced to the fullest by an organization, if the RCM is not applied only on a prioritized list of equipment and systems that will yield optimal return from it. Yet, in order to identify such equipment and systems we have to rely on the screening and prioritization criteria called criticality ranking.

Risk Based approaches to planning and development of asset management strategies have over the years come to stay as effective means to optimize spending on asset integrity while managing safety, environmental and business risks.

Risk Based Reliability Centered Maintenance (RBCM) is a variation of RCM introduced in a bid to obviate the drawback associated with the *ad hoc* nature of the FMEA in the traditional RCM. RBCM is sometimes referred to as Risk Based Maintenance (RBM). Risk Based Inspection (RBI) is one of the core concepts of RBCM/RBM.

3.1 RBCM/RBM Methodology

The RBCM/RBM methodology is based on (i) risk analysis, which consists of the description of failures, their probabilities/frequencies and consequences (ii) risk evaluation, which is based on some risk acceptance criteria (iii) maintenance planning (encompassing the plans for inspections/tests, repair, replacement etc.) based on risk. The results of performed risk analysis regarding probabilities and consequences of failures and risk levels may be adequate input to the RBCM/RBM. However, risk analysis normally concludes on the assumption that relevant maintenance are implemented but do not analyze the applicability and effectiveness of these tasks. Hence, the RBCM/RBM is decisive for the purpose to ensure an effective maintenance to fulfill the risk acceptance criteria.

RBCM/RBM can be regarded as a form of RCM process with the following sequential steps:

- Identification of equipment conditions from research or expert judgment.
  - What type of equipment failures have been experienced or could be experienced?
  - What are the probabilities (likelihood) of these failures occurring?
  - What are the consequences of these failures?
- Estimation of Probability of Failure (PoF) from causal analysis (for e.g. Fault Tree Analysis) or expert judgment by considering specific failure mechanisms.
  - Consider the history of the equipment.
  - Consider the history of similar or identical equipment under same service conditions.
- Estimation of Consequence of Failure (CoF) from consequence analysis (for e.g. Event Tree Analysis) or expert judgment by considering specific failure mechanisms.
- Combination of PoF and CoF into a metric called risk **(i.e. risk estimation)**
- Risk ranking **(i.e. risk evaluation/prioritization)**

- Selection of appropriate maintenance tasks based on ranked risks **(i.e. prioritization of maintenance tasks)**
- Scheduling of maintenance tasks based on criticality and MTBF **(i.e. maintenance interval assessment)**
- Updating information on equipment maintenance history

3.2 Goals of RBCM/RBM

The three main goals of RBCM/RBM are:

- ✓ To identify and estimate risks associated with equipment failure **(Risk analysis)**.
- ✓ To evaluate the risks by virtue of risk ranking and the application of risk acceptance criteria **(Risk evaluation)**.
- ✓ To develop maintenance strategies based on assessed risks, which encompass the plans for condition monitoring, repair, and replacement etc. **(Risk control)**.

3.3 Benefits of RBCM/RBM

The benefits of Risk Based Maintenance include:

- ❖ It is used to optimize maintenance resources, scope and time.
- ❖ It enables decision-making on the extension of life of ageing equipment.
- ❖ It is useful in asset integrity management both in original life and in extended life.
- ❖ It is useful when considering modifications or new designs.
- ❖ It offers suitable ideas regarding the appropriateness and frequency of maintenance tasks.
- ❖ It reduces the probability of unexpected equipment failure and unplanned shutdown.

3.4 The Role of RBM in Maintenance Optimization

An appropriate integration of risk information into the decision-making process (for e.g. the use of a risk decision matrix) could help to optimize maintenance decisions; such decisions could be a plan to increase maintenance efforts on equipment in the order of equipment with higher criticality, i.e. applying maintenance resources to provide a higher level of coverage on the high-risk equipment than on low-risk equipment; this is the first step towards optimizing cost, which implies reduction in cost of safety. The next step is to do further optimization via integration with suitable techniques and models that could optimize maintenance interval or change of strategy (e.g. implementing CBM where TBM has been a typical approach). Hence, enhanced cost optimization is achieved while safety is not compromised.

3.5 A Simple RBM Approach

A simple approach will be to apply **Risk-based scheduled overhaul (RSO)** shown below (in Table 8), which is based on the system risk matrix (Table 5), for decision making and prioritization of overhauls.

Table 8: Example of risk based scheduled overhaul plan (Okoh, 2010)

Risk Level	MTBF (Year)	Prioritized time to overhaul
H	0-1	*e.g.* 1 week
M	1-4	*e.g.* 4 weeks
L	4-20	*e.g.* 24 weeks
VL	>20	*e.g.* 52 weeks

The time to overhaul should be some fraction of the MTBF. For example, if the MTBF is expected to be 3 years, the time to repair could be, say 13 months for high risk and, say 27 months for medium risk. (NORSOK Standard Z-008 rev. 3, 2011)

The risk scale and color coding are as defined in the system risk matrix in Table 5.

4. Integrating RCM with CMMS

RCM may be an effective method in certain situations, but the benefits will not be realized to the fullest if the data applied in its process are deficient. Effectiveness is about doing the necessary thing, but efficiency is about doing something, whether necessary or not, to sufficient quality. RCM, when necessary, has to be done sufficiently well for optimal benefits.

Ruth Olzweski, President of CMMS Data Group Inc. (Olszewski, 2008) establishes a relationship between Computerized Maintenance Management System (CMMS) and RCM. According to her, CMMS contributes critically to RCM analysis by providing equipment data and history. She reiterates that in order for RCM to be successful, CMMS data must be complete and accurate. She concluded that CMMS also allows for action to be taken based on the result of an RCM analysis; and that, in tandem, successful RCM analyses and successful CMMS systems will ensure that a company optimizes its return on assets.

According to (Draft NORSOK Standard Z-008, 2009), the reporting of maintenance data should be based on ISO 14224, which lists a minimum of maintenance information reportage, as shown in Table 9.

Table 9: Minimum required maintenance data reportage (ISO 14224, 2006)

Corrective maintenance (CM)	**Preventive maintenance (PM)**
Failure mode	Condition of equipment before PM work
Failure cause and mechanisms	Man-hours for activity
Equipment outage time	Spare parts used
Spare parts used	Start and finish time
Man-hours for activity	
Start and finish time	

A link between RCM and CMMS is also discussed by (Gabbar, et al., 2003) as shown in Figure 4.

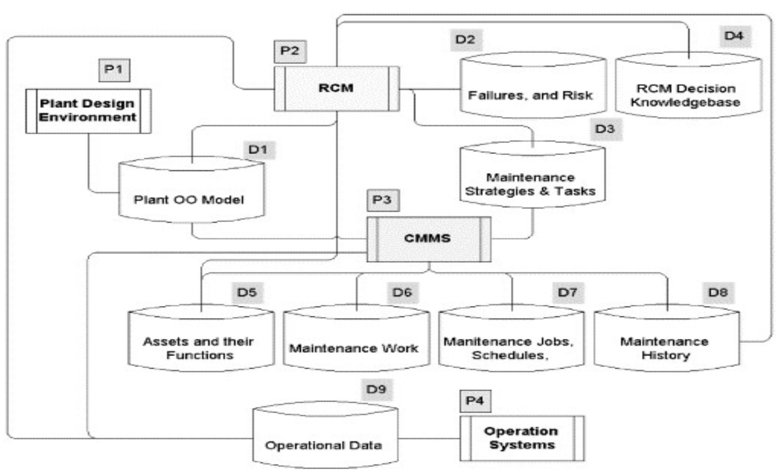

Figure 4: Example of RCM-CMMS integration model (Gabbar, et al., 2003)

Another model suggesting integration between features of RCM and CMMS is shown in Figure 5.

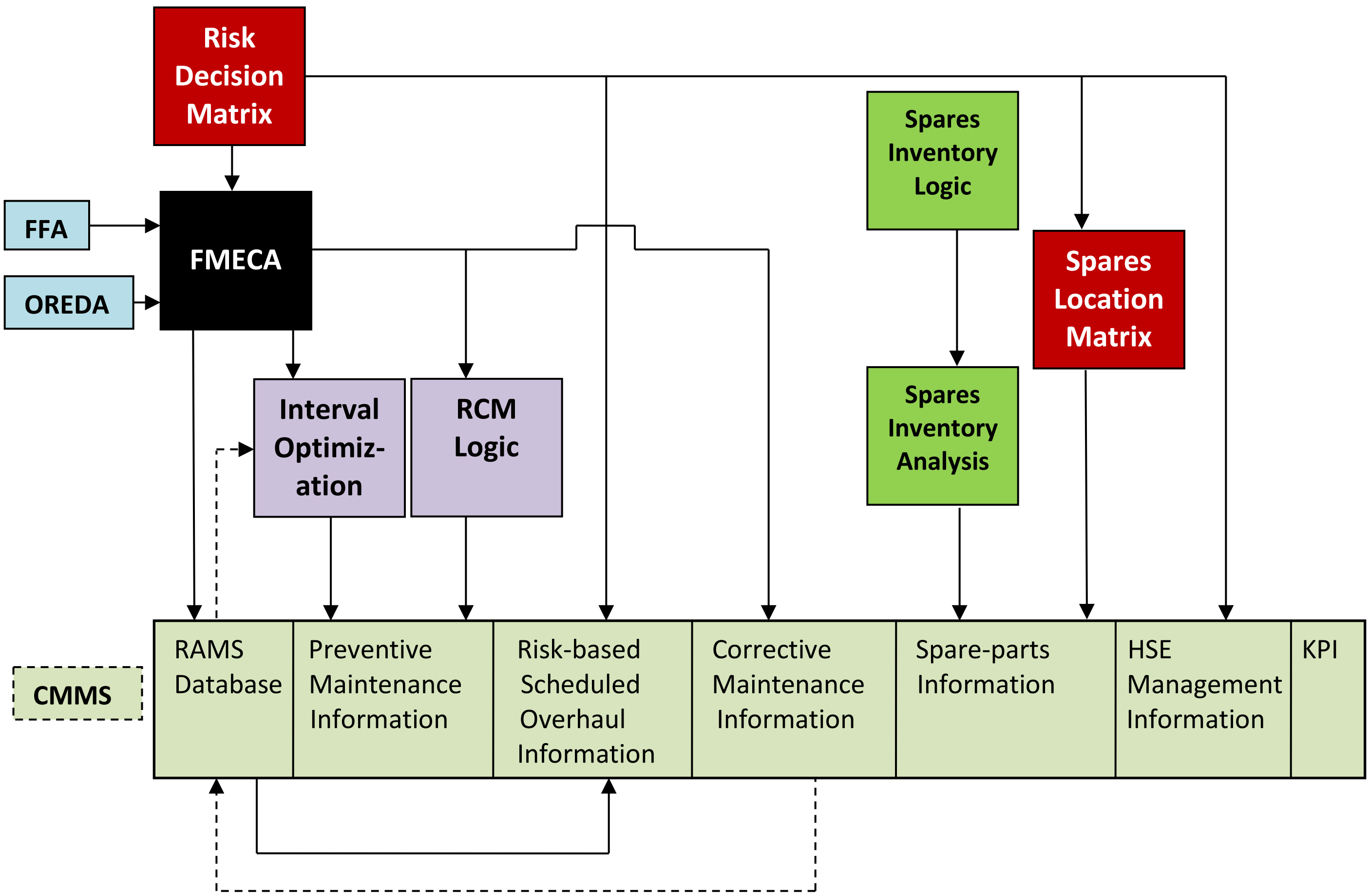

Figure 5: MCDS maintenance optimization model (Okoh, 2010)

The MCDS maintenance optimization model consists of an analytical section (including RCM features) and a CMMS section. The activities of both sections are described as follows:

4.1 Description of the analytical section of a proposed RCM-CMMS model

The analytical section of the MCDS model is where relevant information/data are processed. The functional failures from the FFA serve as the starting point in the FMECA, as failure mode at equipment class level. Some reliability data from OREDA (or other database) such as failure rate and repair rate serve as input for some columns of the FMECA. The risk decision matrix provides information for the criticality part of the FMECA. Reliability data such as failure rate and aging parameter from the FMECA serve as inputs for maintenance interval optimization. The dominant failure modes from the FMECA serve as inputs to the RCM Logic. Information from the risk decision matrix also serves as input for the spare-parts location matrix. Meanwhile, spare-parts analyses are performed by spare-parts inventory logic and spare-parts inventory analysis.

4.2 Description of the CMMS section of a proposed RCM-CMMS model

The outputs from the analytical section of the MCDS model are fed into appropriate parts of the CMMS. Information from the RAMS database part of the CMMS is fed into the risk-based scheduled overhaul part of the CMMS which also receives information from the risk decision matrix. The dotted arrows represent feedback from the corrective maintenance part of the CMMS to update the RAMS database part of the CMMS and further from the RAMS database part of the CMMS to update the interval optimization part of the analytical section.

4.3 Description of the spare parts analysis in a proposed RCM-CMMS model

All the elements of the proposed MCDS, except the spare parts elements, have been described earlier. This section will offer some suggestions regarding spare parts optimization. The objectives are to optimize the location (i.e. accessibility) of spare parts (Draft NORSOK Standard Z-008, 2009) and the sum of (i) cost of running out of stock (which includes production loss due to interruptions, cost of lease, etc. (ii) cost of replenishing stock (which partly depends on the quantity ordered) and (iii) cost of holding stock (which includes interest on capital, depreciation, insurance, obsolescence, storage, etc.) (Kelly, 2006).

4.3.1 Spare parts inventory control analysis (SICA)

This involves different suitable approaches for controlling the inventory of (i) fast-moving spares (> 3 demands per year) (ii) slow-moving spares (< 3 demands per year) and rotables (repairable equipment).

<u>TYPE A PARTS:</u> ***Fast-moving spares (> 3 demands per year) inventory control analysis (FSICA)***

Fast movers have two basic types of control policy, namely (Kelly, 2006):

- Reorder level: replenishment is triggered by stock falling to a preset re-order level.
- Reorder cycle: replenishment decided at regular intervals based on stock review.

Adopting the reorder level policy (RLP) requires that we establish a reorder level (M) to which the stock on-hand (S_{OH}) [i.e. stock held (S_H) plus stock on order (S_{OO})] must be equal. If the latter is less than the former, then a reorder quantity (q) is calculated to replenish the stock. Hence, the reorder level, M, is given by (Kelly, 2006):

$$\boldsymbol{M = DL + k\sigma_D L^{1/2}}$$

Where:

D = Mean demand for the part per unit time
L = Mean lead time
σ_D = The standard deviation of demand per unit time
k = Standard normal variate such that: **F (k) = 1 – X**
Where, X = level of service

Thus, if the desired level of service is say, 96%, then F (k) will be 4% or 0.04
Then k from the standard normal probability density function table is 1.75

F(k) = the probability that demand will not be met during a lead-time, i.e. a stockout will occur.

The desired level of service, *X*, is an acceptable value of the likelihood that demand will be met within any given lead time (Kelly, 2006), and typical values are chosen from 90-99%.

The reorder quantity, *q*, is given by:

$$q = \sqrt{\frac{2DC_O}{C_H}}$$

Where:

C_O = Cost of the replenishment order
C_H = Cost of holding the spare part per unit time

These parameters can be incorporated into Microsoft Excel as shown:

Table 10: Excel worksheet for fast-moving spares inventory control analysis (FSICA) (Okoh, 2010)

Item #	D	L	σ_D	X	k =NORMSINV(X)	M	S_H	S_{OO}	S_{OH}	C_O	C_H	q
1.	12	0.17	3	0.96	1.75	4.14				40	60	4
2.												

<u>TYPE B PARTS:</u> ***Slow-moving spares (< 3 demands per year) inventory control analysis (SSICA)***

A suggestion by (Nahmias, 1996) for modeling slow-moving spares is based on the Laplace distribution and is given by:

$$f(x) = \frac{1}{2\theta} e^{-\frac{|x-\mu|}{\theta}}$$

$$for -\infty < x < +\infty$$

Where:

μ = mean of demand over lead-time
$2\theta^2$ = variance of demand over lead-time = $(\sigma_\mu)^2$

<u>Note:</u> The detailed mathematical process is omitted here.

The reorder point, R, suggested by (Nahmias, 1996) is given by:

$$R = \mu + k\sigma_{\mu}$$

Where:

σ_{μ} = Standard deviation of demand over lead-time

k = As defined earlier

Note: The level of service described under type A parts can also be applied for type B parts.

Hence the reorder quantity, q, is given by:

$$q = \theta + \sqrt{\frac{2AC_O}{C_H} + \theta^2}$$

Where:

A = Annual demand

C_O and C_H = As defined earlier

Finally, *q* is chosen after rounding off to the nearest integer.

These parameters can be incorporated into Microsoft Excel as shown:

Table 11: Excel worksheet for slow-moving spares inventory control analysis (SSICA) (Okoh, 2010)

Item #	μ	σ_{μ}	X	k =NORMSINV(X)	R	θ	A	C_O	C_H	q
1.										
2.										

TYPE C PARTS: ***Rotables (repairable equipment) inventory control analysis (RICA)***

For a rotable (repairable equipment), the reorder quantity, q, is given by (Harper, 1998):

$$q = EAD \cdot (1 - \%REC) \cdot YP + ELTD + Z \cdot \sqrt{ELTD}$$

Where:

EAD = Expected Annual Demand
% REC = The percentage of parts recoverable or repairable (from service statistics or expert judgement.
YP = The number of years to be planned for

ELTD = Expected Lead-Time Demand
Z = Safety factor or standardized variate

The standardized variate (safety factor) used in this model is obtained by virtue of a newsboy model (Nahmias, 1996), in which the model parameters are used to determine overage and underage cost (Harper, 1998). The idea behind this is that more critical parts have higher underage cost and cheaper parts have lower overage cost (Harper, 1998).

Underage cost implies the cost of a spare part being used before the time expected of it to begin service. According to (Inderfurth & Mukherjee, 2008):

Underage cost (C_U) = Shortage cost of rotables spare parts per unit per time period (C_S)

Overage cost (C_{OV}) implies the cost of a spare part being retained in a store beyond the expected period of its use. According to (Inderfurth & Mukherjee, 2008), overage cost is a function of the holding cost (C_H) and run-out time (t) such that:

$$\boldsymbol{C_{OV} = C_H \cdot t}$$

According to (Harper, 1998), a criticality ratio, CR, may be defined as:

$$\boldsymbol{CR = \frac{C_U}{C_U + C_{OV}} = \frac{C_S}{C_S + C_H \cdot t}}$$

The value of CR from the normal distribution table results in the standardized variate (Z)

These parameters can be incorporated into Microsoft Excel as shown:

Table 12: Excel worksheet for rotable inventory control analysis (RICA) (Okoh, 2010)

Item #	EAD	% REC	YP	C_S	C_H	t	CR	ELTD	Z =NORMSINV(CR)	q
1.										
2.										

4.3.2 Spare parts decision logic (SDL)

A simple spare-parts decision logic, which enables the selection of an appropriate method of inventory analysis, is shown as follows.

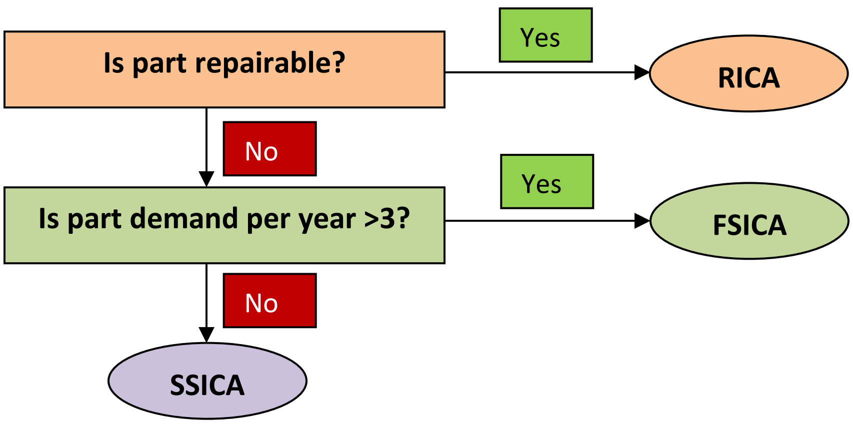

Figure 6: Spare parts inventory control decision logic (Okoh, 2010)

4.3.3 Spare parts location analysis (SLA)

A risk matrix for spare parts recommended by (Draft NORSOK Standard Z-008, 2009) is established to determine the optimum location for spare parts.

Table 13: Example of spare parts location matrix (Draft NORSOK Standard Z-008, 2009)*(adapted)*

Consequence / Demand rate	Low Consequence	Medium Consequence	High Consequence
First line spare parts. Frequently used.	Minimum stock at site **M**	Minimum stock at site, and any additional spare parts at central warehouse.	Adequate stock at site. **H**
Not frequently used.	No stock **L**	Central warehouse, no stock at site.	Central warehouse. Minimum stock at site if convenient.
Insurance spare parts. Seldom never used.	No stock **L**	No stock **L**	Holding optimized by use of risk assessment case by case.

The consequence classes could be defined as follows:

Table 14: Spare parts consequence class description (Draft NORSOK Standard Z-008, 2009) *(adapted)*

Consequence	Description
High	Equipment of a system that must operate in order to maintain operational capability in terms of HSE, production and quality
Medium	Equipment of a system that has installed redundancy, of which either the system or its installed spare must operate in order to maintain operational capability in terms of HSE, production and quality
Low	No consequence for HSE, production or quality.

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