EnFAIT

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ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

D 9.4 – Maintenance Strategy Review (MSR) Specification

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1 Introduction

A Funding Grant was awarded from the European Union's Horizon 2020 research and innovation programme in January 2017 to demonstrate a grid-connected tidal energy array at a real-world tidal energy site, propelling tidal energy towards competing on a commercial basis with alternative renewable sources of energy generation – Enabling Future Arrays in Tidal (EnFAIT). This was in response to the call *LCE-15-2016: Scaling up in the ocean energy sector to arrays* to generate significant learning through demonstration of cost-effective tidal arrays.

This document is produced to describe the Maintenance Strategy Review (MSR) specification and design of the maintenance and condition monitoring programme for the EnFAIT array. It is to be submitted to satisfy deliverable D9.4 of the EnFAIT project and to be also made available for public dissemination.

1.1 Deliverables for Work Package 9 Optimise array reliability, maintainability & availability

The objective of EnFAIT Work Package 9 (WP9) "Optimise array reliability, maintainability & availability" is to design-in reliability and best-practice maintenance regimes to maximise tidal array availability through:

1) Delivering a Design Failure Mode Effect & Criticality Analysis (DFMECA) system (EnFAIT project document D9.2);
2) Conducting a Maintenance Strategy Review (MSR) to mitigate risk and minimise LCoE (EnFAIT project document D9.4 – which is this document);
3) Validation by Reliability Availability Maintainability (RAM) modelling & simulation (EnFAIT project document D9.3);
4) Designing, delivering & demonstrating cost-effective state-of-the-art Condition Monitoring System for tidal arrays (EnFAIT project document D9.5 which is for EnFAIT consortium members only).

See Figure 1 for a graphical representation of the sequence and relationships between these documents.

Note: during the EnFAIT project it was decided to perform the RAM modelling after the MSR. The MSR analysis delivers the requirements for reliability, availability and maintainability. These are then to be validated through RAM modelling, therefore the sequence should be MSR and then RAM.

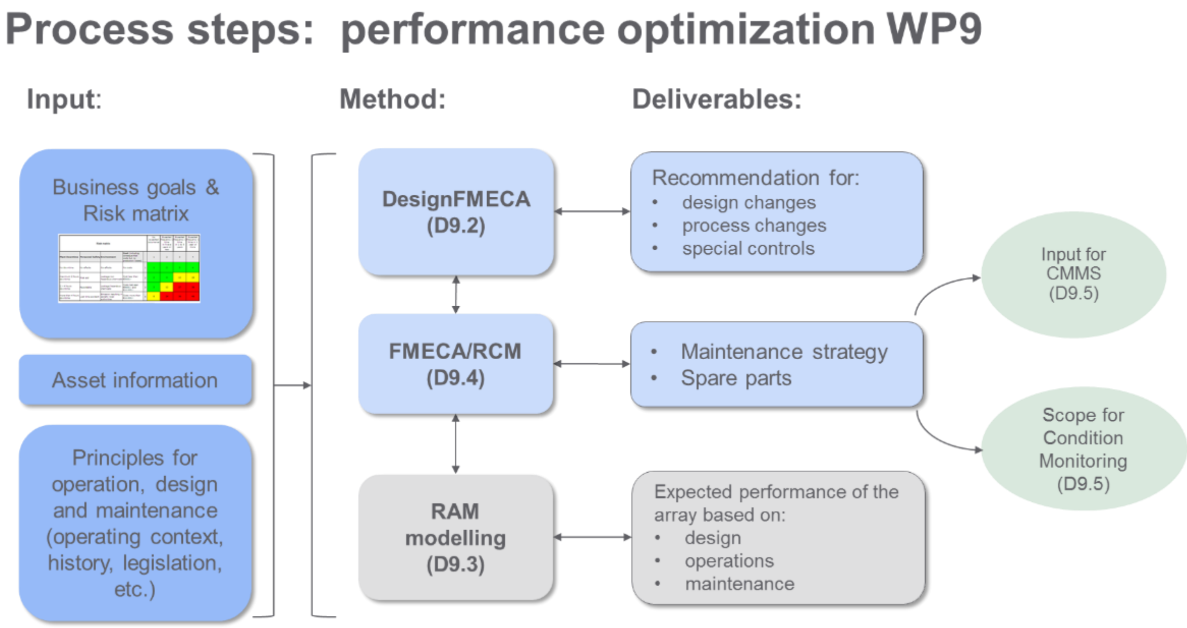


Figure 1: Process steps WP9

1.2 Scope of deliverable D9.4 Maintenance Strategy Review (MSR)

This MSR specification describes the general MSR methodology and its application within the EnFAIT project. The actual data used for, and derived from, this methodology is only shared within the EnFAIT project consortium and European Commission stakeholders, where needed. That data is not published publicly as it contains commercial and technical confidential information.

2 The Maintenance Strategy Review (MSR) methodology

2.1 Maintenance as a contributing factor to LCoE optimisation

The EnFAIT project is carrying out a demonstration of a grid-connected tidal energy array with the aim to provide a step change in Levelized Cost of Electricity (LCoE) for tidal power.

To lower cost per MWh, it is instrumental to optimise the design of the array to the highest reliability and availability levels possible. The reasoning behind this, is that a highly reliable system suffers less breakdowns, resulting in lower maintenance and repair costs. Also, a lower number of breakdowns plus shorter repair times, results in a larger net operating time (i.e. higher availability). These performance indicators affect LCoE.

A generally accepted performance indicator for plants is Overall Equipment Effectiveness (OEE, %). It is calculated as follows:

- OEE = Availability (%) X Performance (%) X Quality (%)

Where:

- Availability = (MTBF) / (MTBF+MTTR)
  - MTBF: Mean Time Between Failures = average operating time between failures
    = (Total up time) / (number of breakdowns)
  - MTTR: Mean Time to Restoration = average of the times to restore the function of the asset
    = (Total down time) / (number of breakdowns)
- Performance = actual power output / nominal power output
- Quality (measure for quality of output) = 1, as for energy production there are no MWh's that do not pass quality standards or need reworking (as can be the case for discrete products)

Therefore, for power plants:

- **OEE = Availability (%) X Performance (%)**

Performance of tidal power plants is influenced by the tides and currents, hence the highest OEE can be reached by increasing the availability through increasing the MTBF and lowering the MTTR.
MTBF is defined by the arithmetic mean value of the reliability function R(t), which can be expressed as the expected value of the density function ƒ(t) of time until failure:

$$\mathrm{MTBF} = \int_0^\infty R(t)\,dt = \int_0^\infty t f(t)\,dt$$

So, by **increasing reliability**, **availability is increased** and thus **OEE is increased**.

Reliability is influenced by the design, manufacture and assembly of an asset. This is called intrinsic or inherent reliability. Therefore, during the design phase, a Design Failure Mode Effect & Criticality Analysis (DFMECA) is performed to identify any inherent failure causes which can be designed-out, or where the chances of failures can be minimised by defining manufacturing and assembly quality requirements. (Refer to EnFAIT Deliverable D9.2 Design Failure Mode Effect Analysis (FMEA) Report, November 2017.)

During the operate and maintain phase of a power plant, it is important to perform the right maintenance at the right time to positively influence MTBF and MTTR. This is covered by the FMECA / RCM (Reliability Centered Maintenance) analysis which also focuses on preventing failures as much as possible through preventive maintenance. See
Figure 2: Lifecycle management below for a graphical representation of the whole lifecycle approach.

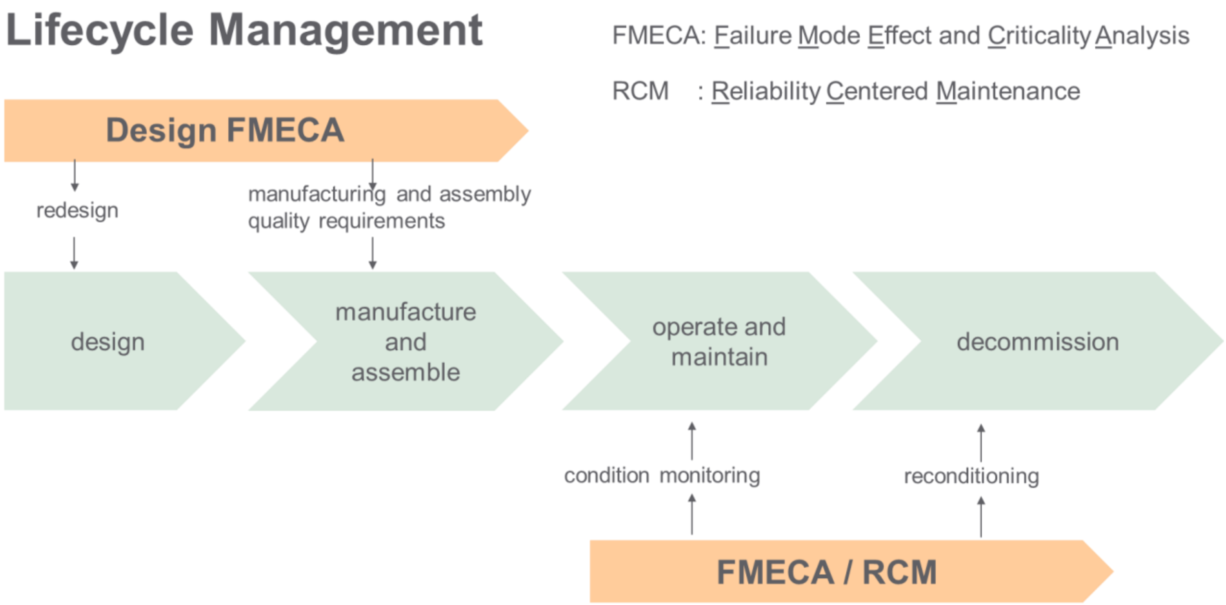


Figure 2: Lifecycle management

Through FMECA / RCM analysis, a maintenance strategy is designed which assigns the appropriate maintenance type to each failure cause – see Figure 3 below.

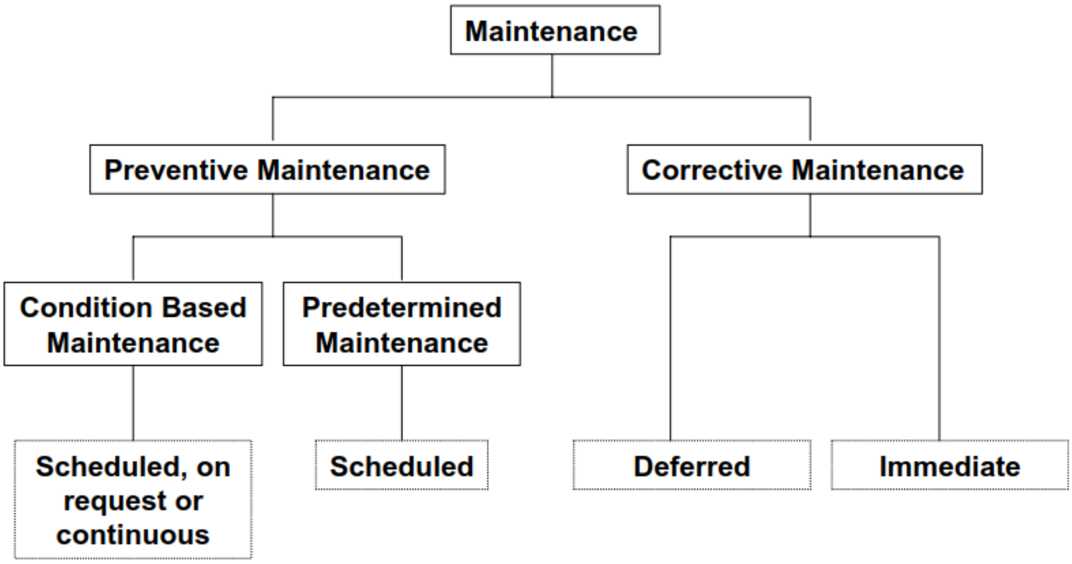


Figure 3: Maintenance types (source: NEN-EN 13306, p. 20)

2.2 Definition of a Maintenance Strategy Review

A Maintenance Strategy Review is a proven methodology to engineer an actionable full lifecycle maintenance plan for the tidal array systems and components. Given the absence of reliability history in the tidal sector, use is made of SKF's Asset Management Support Tool (AMST), which facilitates and documents a thorough FMECA and RCM analysis.

Through FMECA, failure modes & causes are identified, their effects and associated risk levels (or: criticality ranking) related to the array business drivers/plant economics. Through RCM analysis, specific maintenance & condition monitoring tasks are identified to prevent critical failure modes. Thus, the greatest risks from a commercial, health, safety, environmental and cost perspective are mitigated. The MSR delivers a comprehensive data set, including an asset inventory including tag hierarchy, the specification and design of a value adding maintenance and condition monitoring programme for the array that delivers tangible cost benefits and advises on spares strategy.

The MSR process is aligned with the following standards:

- ISO 55001:2014 Asset Management
- ISO 31000:2018 Risk Management
- NEN-EN 13306 (en) Maintenance - Maintenance terminology
- NEN-EN 15341 (en) Maintenance - Maintenance key performance indicators
- NEN-EN 16646:2015 Maintenance - Maintenance within physical asset management

3 Maintenance Strategy Review best-practice

3.1 Introduction

The aim of this best practice is to implement a consistent application of the Maintenance Strategy Review methodology in the EnFAIT project.

3.1.1 Abbreviations

AMST	Asset Management Support Tool
CBM	Condition Based Maintenance
CMMS	Computerised Maintenance Management System
FMECA	Failure Mode, Effect & Criticality Analysis
MOD	Modification
MRO	Maintenance, Repair and Overhaul
MSR	Maintenance Strategy Review
MTBF	Mean Time Between Failure
NHL	Next Higher Level
PM position	Maintenance Plan Position
RASCI	Responsible Accountable Supporting Consulted Informed
RCM	Reliability Centered Maintenance
RTF	Run To Failure

3.1.2 Definitions

Asset register:	Functional breakdown of the asset to the level of maintainable items.
Condition Based Maintenance (CBM)	Maintenance activities consist of the periodical inspection or online measurements of the technical condition of the installation. Depending on the technical condition of the installation, repair activities will be planned or carried out.
Equipment	SKF definition: 'Business object "Equipment" is an individual, physical object that is to be maintained independently (maintainable item)'.
Failure Finding Maintenance (FFM)	Maintenance activities consisting of the functional testing or inspection of a hidden feature of the installation. Depending on the test results, repairs will be carried out.
Functional location	SKF definition: 'A functional location is an organizational unit within Logistics that structures the maintenance objects of a company according to functional or process-related criteria. A functional location represents the place at which a maintenance task is to be performed'.
Inventory management	SKF definition of Inventory Management: 'All activities considering managing (requesting, receiving, issuing, monitoring) of MRO inventory to ensure a correct, complete, timely and cost effective provision of materials required to perform plant maintenance'.
Management of Change	SKF definition of Management of Change: 'All activities required to maintain a complete and consistent set of documentation, securing it provides correct information about equipment as it is operated'.

Modification (MOD)	Combination of all technical, administrative or organizational actions with a view to change a function of any equipment or process.
Risk matrix	A matrix combining consequences and probability into a risk classification according to a qualitative approach. The risk matrix has been standardized and is a binding - leading performance requirement for the company management.
Run To Failure (RTF)	Fault is resolved when it occurs, no planned actions.
Scheduled Maintenance (SM)	Maintenance activities take place based on the usage of the installation (calendar time, operating hours, etc.) and are independent of the technical condition of the installation
Work order management	SKF definition of Work order management: 'All activities considering managing (requesting, reviewing, issuing, executing, controlling and analysing) work orders to effectively perform maintenance'.

3.1.3 RASCI

This best practice uses RASCI to establish the roles and responsibilities of the employees involved within the organization.

R: Responsible (the person who carries out the task correctly)
A: Accountable (the person who is ultimately responsible for the result)
S: Supportive (assigned to support the person carrying out the task)
C: Consulted (the person who is consulted).
I: Informed (those who must be informed about the result).

The rules for RASCI are:

- For each activity a person with a certain role must be Responsible
- For each activity a person with a certain role must be Accountable

As the organisation for operating and maintaining the full tidal array is yet to be established, the activities in the flowchart are not yet assigned to roles. These flowcharts should be considered when designing the future organisation to manage the EnFAIT assets.

3.2 MSR process flow

The Maintenance Strategy Review process steps 1 to 5 have been included in this best practice.

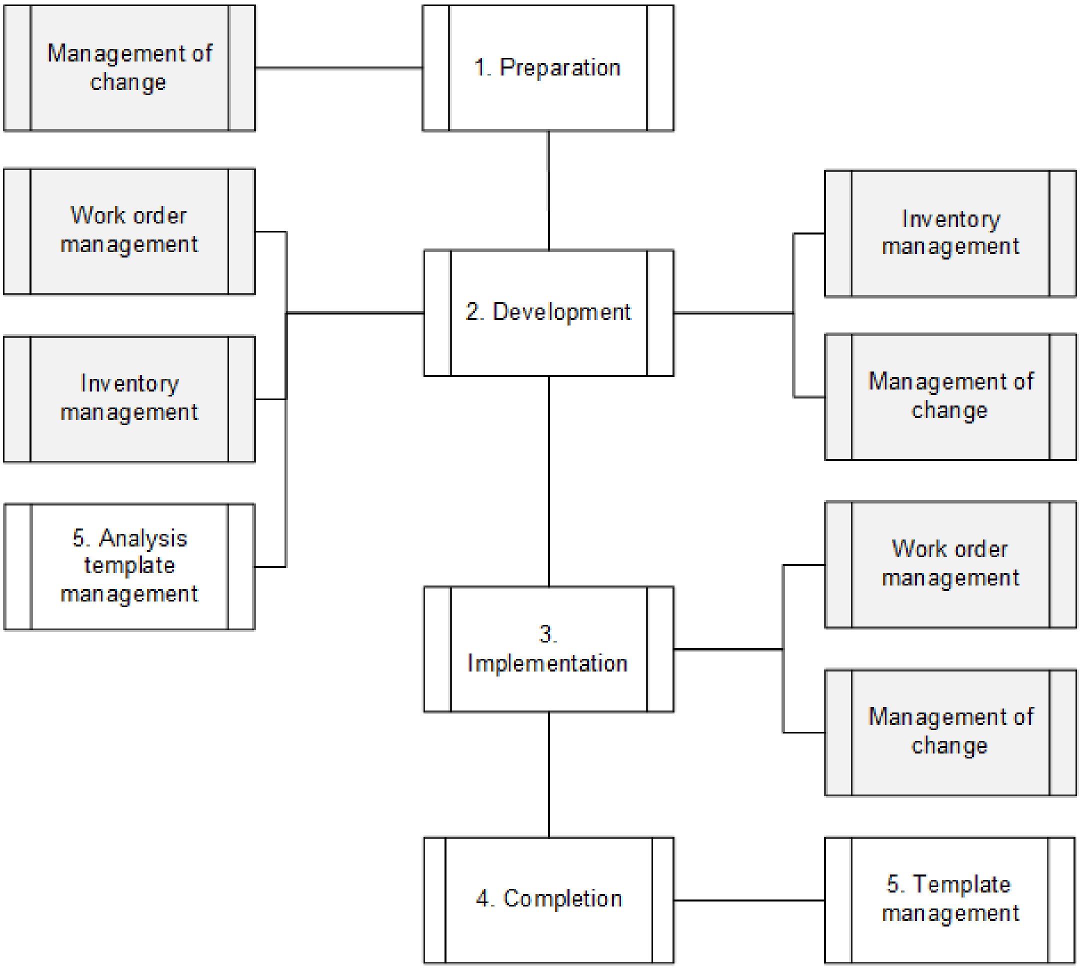


Figure 4: Flowchart for Maintenance Strategy Review

The following processes are not part of the scope of this best practice:

- Management of Change:
    - Input MSR: CMMS asset register, modified systems of equipment, required documentation as described in section 1.6.
    - Output MSR: update CMMS asset register, update risk classification, modification proposals.
- Work order management:
    - Input MSR: current planned and corrective maintenance.
    - Output MSR: update of planned maintenance.
- Inventory management:
    - Input MSR: current spare parts.
    - Output MSR: advice regarding spare parts.

3.3 Preparation

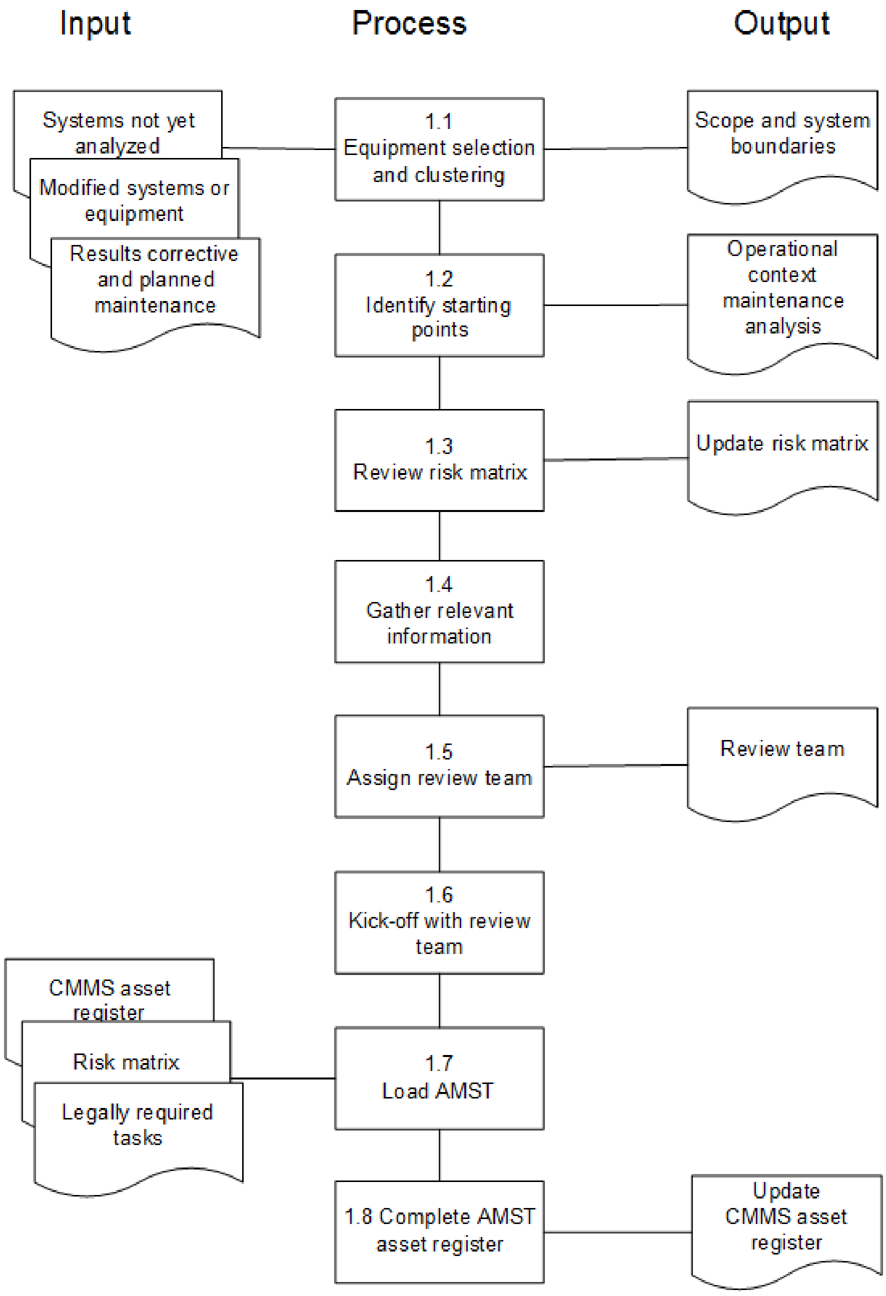


Figure 5: Flowchart MSR Preparation

3.3.1 Equipment selection and clustering

The basis for the equipment selection is an overview of systems and/or equipment types:

- Those that have not been included in MSR yet;
- Those that have been changed;
- Those that must be assessed based on results of corrective for planned maintenance;
- Those of which an MSR has not been assessed for more than 5 years.

The equipment selection is carried out on the basis of objectives and priorities for systems and/or equipment types in the area of:

- Health, Safety or Environment;
- Legislation or regulation, permits, internal requirements, etc.
- Production (downtime, efficiency, quality, costs).

The following is established during the equipment selection:

- Which systems or equipment (types) must be analysed in which order.
- From the perspective of efficiency, which systems or equipment (types) do not need to be analysed.

Prioritization for EnFAIT: reduce Levelized Cost of Electricity (LCoE) for tidal power.

Equipment items are clustered after the equipment selection. The cluster is a collection of a maximum of 100 equipment items of a system or of the same equipment types. Clusters are used to go through the entire MSR process for a number of equipment items from preparation to completion in a few months.

The content of clusters is recorded by the enumeration of the pertinent equipment items or by assessing the system boundaries, together with the reasons for the cluster equipment selection.

3.3.2 Establishing requirements

A cluster needs the requirements for the operational context and maintenance, to be recorded in a document.

The following is recorded for the operational context:

- Functions of system;
- Legal requirements and standards;
- Internal (quality) requirements and standards;
- Preconditions for business operations;
- Preconditions and response times for maintenance;
- Redundancies, including maximum downtime for planned and corrective maintenance;
- Consequence of failures at system level.

For the maintenance analysis, a data analysis of the fault registration, maintenance costs and downtimes is used to determine equipment with the highest repair cost (cost drivers) and equipment with the longest downtime (performance killers). Note: the term “bad actors” is used as a collective term for cost drivers and performance killers. Equipment with the most frequent faults (irritators), is usually disregarded.

With respect to the requirements for maintenance, the following is also recorded:

- Well-known technical threats;
- Recent or planned modifications;
- Recent or planned changes in business operations;
- Obsolete components;
- (Legally) required sources with respect to planned maintenance tasks;
- (Economic) residual life.

Main requirements for design, operations and maintenance of EnFAIT tidal turbine array		
1	**Functions of the array:**	**Produce electricity at competitive cost level.** ***Note: goal of the project is to demonstrate a 40% reduction in LCoE***
	Tidal current velocity	Max 2.9 m/s
	Wave height	n.a.
	Water depth	Clearance 29 – 35 m
	Water temperature	3 - 19°C (design temp)
	Outputs	t.b.c. MW/h per year
	Legal requirements and standards	t.b.c.
	Redundancies	None
	System boundaries	Turbines and grid included, vessels and other auxiliary equipment excluded
	Risks	• Lifetime of the seal (max. 2 years) is decisive for maintenance interval • Lifetime oil and grease • Contamination surface
	Risk matrix	Refer to risk matrix in section 3.3.3. The risk matrix was established in January 2018, and may be subject to change over time to record any changes in business conditions
2	**Availability & Reliability requirements:**	
	Initial requirements for availability	Refer to risk matrix in section 3.3.3. Cost of turbine complete loss: t.b.c. Downtime: t.b.c.
	Initial requirements for reliability	• There will be unplanned maintenance needed on average once every 2 years (i.e. 10 over 20-year life) – cost reduction opportunity through reliability improvements (key objective of WP9)
	Number of planned stops + duration	• Planned service of each turbine every 2 years (i.e. 9 over 20-year life) • Two of these services will be “major” and the rest “minor” • Multiple turbines will be deployed and recovered in a single offshore operation – note that this impacts on availability… optimum strategy to be developed as part of WP9
	Number of allowable trips + duration	unidentified
	Simultaneity downtime	unidentified
	Required uptime	90% incl. planned and unplanned maintenance
	Maximum downtime per turbine	unidentified
	Maximum downtime total array	unidentified
	Cost for submerging	In the range of € t.b.c.

3.3.3 Risk matrix checks

The risk matrix is used for prioritizing faults in accordance with the qualitative approach based on the scope of the consequences and probabilities. The result of a risk matrix is a risk classification.

The risk matrix has fixed categories for the risk classification:

A: Unacceptable Component
B: Critical Component
C: Important Component
D: Breakdown Component

Low risk:	Regular maintenance (e.g. cleaning, lubricating)
Medium risk:	Inspection offshore every two years (regular maintenance interval)
High risk:	Preventive / predictive maintenance
Extremely high risk:	Modification

For EnFAIT, the following criteria have been included in the risk matrix:

- Safety
- Environment
- Availability
- Cost of repair

	Effects				Likelihood				
					Extremely unlikely	Improbable	Occasional	Probable	Frequent
	Safety	Environment	Availability	Cost of repair	more then 1 x 20 years	between 6 and 20 years	between 2 and 6 years	between 0,5 - 2 years	more than 1x 0,5 years
Insignificant	No effect	No Effect	No effect on electricity generation	Less than £[A] (repair can wait till next surfacing)	low risk	low risk	low risk	medium risk	medium risk
Minor	First Aid Injury or one ore more Medical Treatment Injuries	Local effect	Turbine offline for 6 hours (next slack water)	Between £[A] and £[B] (+ cost for surfacing)	low risk	low risk	medium risk	high risk	high risk
Moderate	One ore more Lost Time Injuries	Notification to the government	Turbine offline for 2 weeks (next neap tide)	Between £[B] and £[C] (+ cost for surfacing)	low risk	medium risk	high risk	high risk	extremely high risk
Major	One ore more significant Lost Time Injuries	Government penalty	Turbine offline 6 month (replacement of long-lead-time component)	Between £[C] and £[D] (+ cost for surfacing)	medium risk	high risk	high risk	extremely high risk	extremely high risk
Catastrophic	One or more fatalities	Loss of Licence to Operate	Complete loss of turbine	More than £[D] (+ cost for surfacing)	high risk	high risk	extremely high risk	extremely high risk	extremely high risk
				Note: costs [A], [B], [C], [D] are known but confidential					

green	low risk	Regular maintenance (cleaning, lubricating)
orange	medium risk	Inspection offshore every two years (regular maintenance interval)
red	high risk	Preventive / predictive maintenance
dark red	extremely high risk	Modification

Figure 6: Risk matrix for EnFAIT tidal array turbine

Note: the risk matrix was established in Jan-2018, and may be subject to change over time.

3.3.4 Creating a Review Team

The Review Team is created per cluster and consists of people from the following disciplines:

- Reliability & Maintenance Engineer, also facilitator;
- Senior Operator;
- Senior Mechanic;
- Work Planner;
- (Process) Engineer (especially with new constructions or modifications).

Review Team members are selected for a cluster based on their:

- Knowledge of operations and maintenance;
- Authority to make decisions regarding planned maintenance tasks and spare parts;
- Required support for changes in planned maintenance and spare parts;
- Necessary exchange of knowledge for 'less' experienced colleagues

3.3.5 Kick-off with Review Team

Prior to the development and review of a cluster, a kick-off session is held in which the following will be explained to all parties involved:

- Equipment selection in cluster;
- Principles;
- Planning;
- Composition of Review Team.

Immediately after the kick-off meeting, a workshop is held, if necessary to explain the methods used for the development, the concepts applied and the expected input during the review.

3.3.6 Collecting relevant information

Regarding the equipment in the cluster, it is essential to use the following documentation and maintenance history during the MSR:

- Process description;
- Operating manual;
- Technical drawings;
- Instrumentation loops / Component interaction (logics) / Cause and Effect diagram;
- Overview of legally required planned maintenance tasks;
- Overview of current spare parts/spare parts lists (bill of material);
- Overview of current planned maintenance tasks;
- Manufacturer (OEM) manual.

3.3.7 Configuring AMST

To facilitate MSR, the SKF Asset Management Support Tool (AMST) is used.
AMST is configured for use with:

- Risk matrix;
- Up to date version of asset register of the equipment in the cluster;
- Up to date legally required planned maintenance tasks for the equipment in the cluster;
- Selection list for the party responsible for the task in accordance with up to date or default Task Work Centers in CMMS if available);
- Task Type selection list in accordance with up to date or default Task Activity Types in CMMS;
- Task Condition selection list in accordance with up to date or default Task System Conditions in CMMS;
- Review Team members involved with the review of the cluster.

During the project, the asset register (Functional location levels in accordance with PM Standardization aspects) is copied into the AMST asset register as follows:

<table>
<tr><th>Register level</th><th>AMST</th></tr>
<tr><td>Factory / plant</td><td>Facility</td></tr>
<tr><td>Area level</td><td rowspan="3">Systems</td></tr>
<tr><td>Section</td></tr>
<tr><td>Process</td></tr>
<tr><td>Sub process</td><td rowspan="2">Subsystems</td></tr>
<tr><td>Sub-sub process</td></tr>
<tr><td>Function</td><td rowspan="2">Asset</td></tr>
<tr><td>Equipment installed</td></tr>
</table>

The MSR analyses are linked to the lowest functional location in the asset register.

For EnFAIT, no final selection of the CMMS to be used has been made at this time. This will be part of project document D9.5 which follows after this document D9.4.
Therefore, functional locations have not yet been established for all equipment items. The approach is to subsume the CMMS equipment items under AMST and to run the analyses on these items. For the time being, this best practice therefore refers to an equipment analysis.

3.4 Development

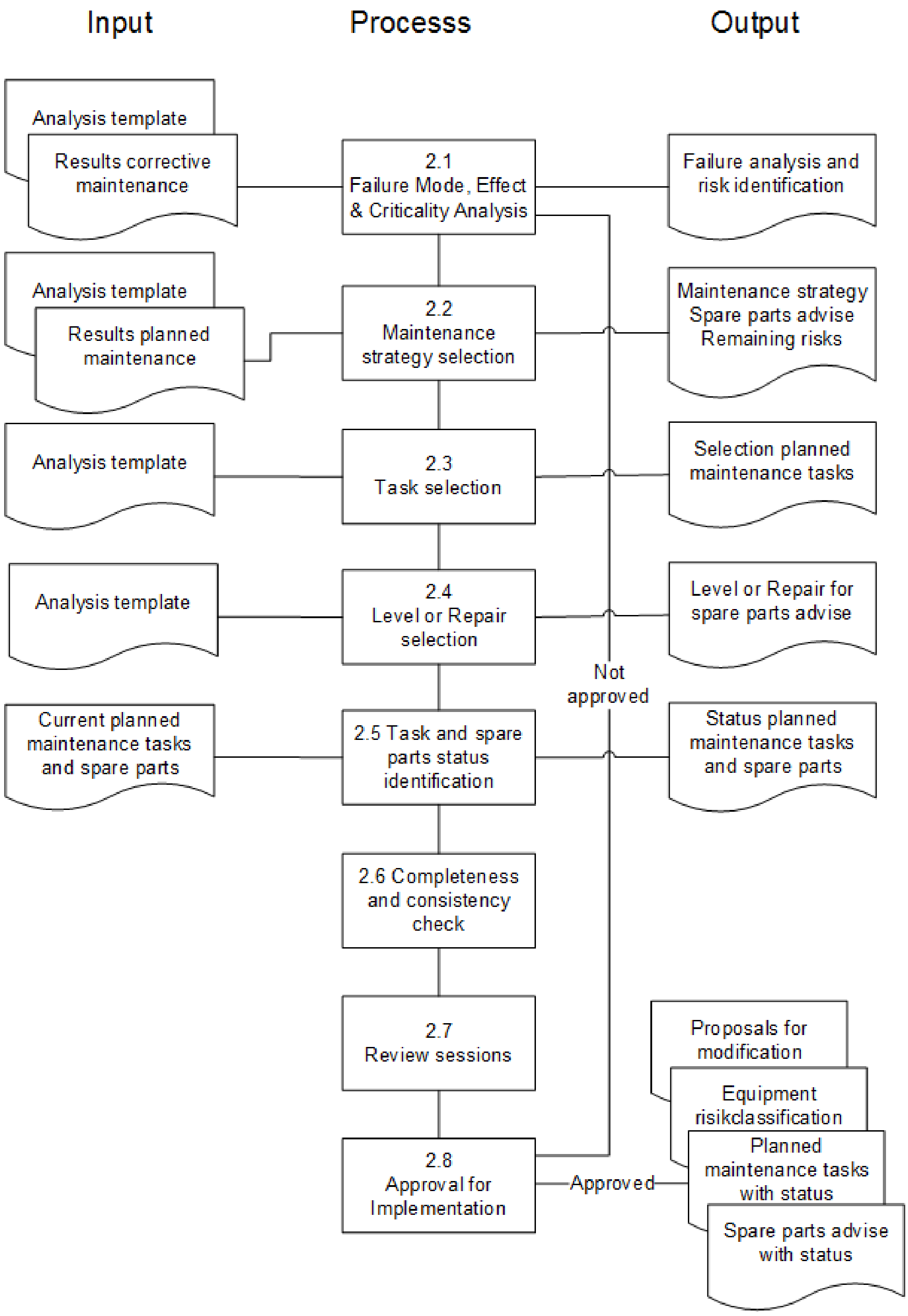


Figure 7: Flowchart MSR Development

3.4.1 Failure Mode, Effect & Criticality Analysis

The FMECA analysis is carried out by means of the following steps:

1. Functions:	What are the functions and associated desired standards of performance of the asset in its present operating context?
2. Functional disturbance:	In what ways can it fail to fulfil its functions?
3. Failure modes:	The way in which an asset fails, resulting in a functional disturbance
4. Cause of the failure modes:	Which process or mechanism causes each functional failure?
5. Effects:	What happens when each failure occurs?
6. Consequences:	In what way does each failure matter?

1. Identify the **function(s)** that the asset is intended to perform (what the user wants it to do). What users expect assets to be able to do can be split into two categories:
    - primary functions, which summarize why the asset was acquired in the first place. This category of functions covers issues such as speed, out-put, carrying or storage capacity, product quality and customer service.
    - secondary functions, which recognize that every asset is expected to do more than simply fulfil its primary functions. Users also have expectations in areas such as safety, control, containment, comfort, structural integrity, economy, protection, efficiency of operation, compliance with environmental regulations and even the appearance of the asset,

2. Identify the **functional disturbance** (or: failure): an asset that no longer performs its specified function.
   To be described as a failed state:
    - Complete loss of the function
    - Under-performance
    - Over-performance
    - Unintended function

3. Identify the **failure mode**: the event that causes the functional failure (something has happened with the asset resulting in a functional failure).

   Failure modes include those failures which have occurred on the same or similar equipment operating in the same context, failures which are currently being prevented by existing maintenance regimes, and failures which have not happened yet but which are considered to be real possibilities in the context in question.

   Lists of failure modes incorporate failures caused by deterioration or normal wear and tear. However, the list should include failures caused by human errors (on the part of operators and maintainers) and design flaws so that all reasonably likely causes of equipment failure can be identified and dealt with appropriately.

4. Identify the **cause of the failure mode**:

   Identify the most plausible circumstance e.g. physical, mechanical or chemical process, resulting in a failure mode.

5. Identify **failure effects** for every failure cause: what happens when the asset fails?

   This should be described on the following levels:
   - Local effect (asset level)
   - Next higher level effect (sub system level)
   - End effect (system level)

   These descriptions should include all the information needed to support the evaluation of the consequences of the failure, such as:
   - what evidence (if any) that the failure has occurred
   - in what ways (if any) it poses a threat to safety or the environment
   - in what ways (if any) it affects availability
   - what physical damage (if any) is caused by the failure
   - what must be done to repair the failure

6. Identify the **consequences of failure**:

   Each failure mode affects the organization in some way, but in each case, the effects are different. They may affect safety, environment, operations or cost of repair (consequence factors). They will all take time and all cost money.

   Criticality is the multiplication of the consequence factor and the probability factor, where probability is the likelihood that a failure cause will occur resulting in the failure mode.

   The risk of the failure mode (and therewith the criticality of the asset) is determined using the NOVA risk matrix (see Figure 6: Risk matrix for EnFAIT tidal array turbine); by choosing one of the listed consequences for each business goal (safety, environment, operations and cost of repair) and selecting the likelihood.

   - If the risk is low (green), only regular maintenance is done (cleaning and lubricating).
   - If the risk is medium (orange), inspection offshore every two years (regular maintenance interval) will be scheduled.
   - If the risk is high (red), preventive (condition based or predetermined) maintenance tasks are applicable.
   - If the risk is extremely high (dark red), the asset has to be modified because the asset is not suitable to fulfil its function.

AMST screen 'Identification'		
Asset Id	Unique identification number, generated by AMST	n/a
Asset Code	Code used in customer CMMS / ERP Note: duplication should be avoided	Mandatory
Description	Asset description as used in customer CMMS / ERP Note: SAP max 40 characters	Mandatory
Asset class	• Facility: highest available level (1.client, 2.site, 3.plant) • System: functional breakdown level which is not a maintainable item • Subsystem: used the same way as System • Asset: maintainable item, analysis should be done at this level • Loop/group: special Asset, used as a representative asset for similar assets, used for efficient reporting 'System function' and 'System functional failure' are concepts from another analysis method and should not be used	Mandatory
Asset type	If Asset class is Loop/group, chose 'Typical' For all other Asset classes, leave empty	Mandatory
Risk matrix	Selection of the risk matrix applicable to the analysis	Mandatory
Review status	• Choose from the following analysis status options: • New: Asset created or uploaded, but no analysis started • Concept: analysis has been drafted • Internally reviewed: analysis reviewed by colleague • Externally reviewed: analysis has been approved for implementation • Final: planned maintenance tasks and spare parts have been handed over for implementation • Copy: analysis is identical to Typical analysis in loop/group. Tasks should be manually copied from Typical. • Removed: equipment is no longer in service; all children should be Removed as well	Mandatory
Function	Function of the equipment within the system, including performance requirements, e.g. minimum flow It is possible that an equipment has multiple functions	Mandatory, except for members of Loop/group
Op mode	Operational mode, circumstances and principles applying to the equipment, e.g. 24/7 or batch operation	Optional
Environment	Environmental requirements, e.g. License To Operate	Optional
History	Equipment history, e.g. modifications	Optional
Reference	Reference to equipment documentation, e.g. maintenance manual	Optional
P&ID	PID drawing number Mandatory if a PID is available	Mandatory

OEM Model No	Original Equipment Manufacturer model number	Optional
OEM Manufacturer	Original Equipment Manufacturer	Optional
Revision No	Revision number of analysis Small textual changes in an analysis do not require the version number to be updated AMST does not keep replaced analysis versions in the database	Optional
Date	Date of the latest revision of the analysis Small textual changes in an analysis do not require the date to be updated	Optional
Team	Predefined team that performed the analysis Not used	n/a
New asset	Indicates new equipment, which not yet exist in the CMMS / ERP	Mandatory
Critical	Equipment is critical for at least one failure cause (see RCM tab)	n/a
RTF	Maintenance strategy is Run To Failure for all failure causes	n/a
Tab General, field Remark	This field may be used for outstanding questions or action items with respect to the analysis. The other fields on tab General are not used.	Optional
Tab Members or tab Groups	If the asset is a Loop/Group, the tab Members exists and shows the assets that are linked to the typical. This data can be edited. If the asset is linked to a Typical, the tab Group exists and shows the Typical. This data can be edited.	Optional
Tab RBI	Risk Based Inspection according to T260 standard Not used, possibly not available (no license)	n/a
Tab Cost	Not used	n/a
Tab Analyse team	Not used	n/a
Tab Commitment	Selection of legal requirements and standards or internal (quality) requirements and standards applicable to the analysis (if applicable)	Optional
Tab RCM User Defined – Info	Tag: Physical tag number, e.g. P-1940A Empty if customer used Asset Code for the tag Type: Asset type, e.g. Pump Info 3: to be defined for customer and/or project Info 4: to be defined for customer and/or project Info 5: to be defined for customer and/or project Info 6: to be defined for customer and/or project	Mandatory Mandatory t.b.d. t.b.d. t.b.d. t.b.d.

AMST screen 'RCM analysis'		
Functional disturbance	Specific failure to execute the Function as described on the Identification tab Specify as: too much, too little, does nothing, unintended functions (leakage)	Mandatory
Failure mode	Description of how an equipment component fails, resulting in a functional disturbance. An equipment may have one or more failure modes. Specify as component + defect e.g. impeller damaged. Choose from standard failure modes in List.	Mandatory
Failure mode code	Effect code, is available	Optional
Cause of failure mode	Description of a physical, chemical or mechanical process resulting in a failure mode. A failure mode may have one or more causes. Specify using terms such as corrosion, fatigue, overload etc. Choose from standard failure causes in List.	Mandatory
Cause code	Damage code, is available	Optional
Location	Location of the cause of failure mode in the equipment.	Optional
Corrosion margin	Not used	n/a
MTBF and time unit	Failure interval of the cause of failure mode, evaluated without planned maintenance	Mandatory
Comment regarding failure interval	Source based on which the failure interval of the cause of failure mode is determined	Mandatory
Local effect	Effect of the cause of failure on equipment level	Mandatory
NHL effect	Effect of the cause of failure on a (next) higher level (NHL) in the functional breakdown structure	Mandatory
End effect	Effect of the cause of failure for the plant Choose from standard end effects	Mandatory
Downtime including time unit	Loss of production as a result of the failure, evaluated without available spare parts or third party contracts	Mandatory
Corrosion Allowance	Not used	n/a
Remark	Any comment on the analysis of the failure cause, e.g. redundancy or accuracy of downtime estimate	Optional
Spare Parts Cat.	Use 'Y' if spares are advised, or 'N' if no spares are necessary Reasons to advise spares are: • Necessary reduction of downtime to reduce risk to non-critical level; • Cost effectiveness, cost of saved downtime is expected to clearly exceed spare part price. If 'Y', specify the spares on a corrective task	Mandatory

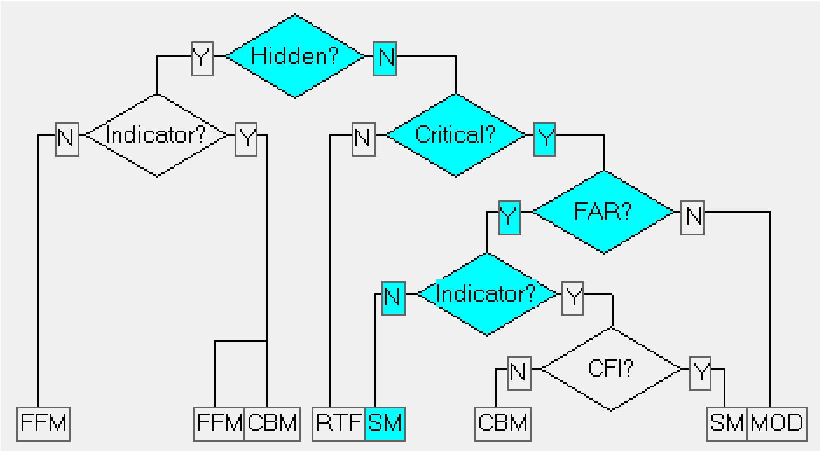
Spare Parts Advise	Level of Repair: • Repair inline, using customer supplied parts or assemblies (e.g. valve actuator) • Repair inline, using no customer supplied parts or assemblies • Repair in customer workshop • Repair off-site by contractor, using customer supplied parts or assemblies • Repair off-site by contractor, using OEM supplied parts or assemblies • Exchange of entire equipment, replaced by customer supplied equipment • Exchange of entire equipment, replaced by third party supplied equipment	Optional
Spare Parts Remark	Any comment on the spares advise, like background of Level of Repair or potentially shorter delivery times	Optional
Risk classification based on risk matrix	Effect of the cause of failure mode is determined for each criteria in the effect matrix. The highest effect in the effect matrix in combination with the probability yields the risk.	Mandatory

3.4.2 Maintenance strategy selection

A maintenance strategy is selected for each equipment cause of failure. The following maintenance strategies apply:

- Failure finding maintenance (FFM)
- Condition based maintenance (CBM)
- Scheduled maintenance (SM)
- Run to failure (RTF)
- Modification (MOD)

The maintenance strategy selection is carried out by means of the following steps in AMST:

AMST screen 'RCM analysis'		
RCM decision tree	For each cause of failure, the RCM decision tree is completed. The decision tree gives a suggestion for the maintenance strategy.  Figure 8: RCM decision tree The following failure characteristics have been included in the decision tree: • Hidden? Is the failure detectable under normal operating conditions at the moment the failure occurs? • Critical? Is the cause of failure at a critical level according to the risk matrix? • Failure Age Related? Is the cause of failure mode age-related (degradation process)? A failure is not age-related if it can happen at random (electronics) • Indicator? Can the cause of failure mode be predicted by trend measurements for a certain indicator? • Constant Failure Interval? Is it a certainty that the failure will manifest itself after a known and constant period (or a fixed number of operating hours)?	Mandatory
Maintenance strategy selected	Selection of the maintenance strategy for the cause of failure.	Mandatory
Maintenance strategy motivation	If the selected maintenance strategy deviates from the maintenance strategy suggestion from the RCM decision tree, the justification will be recorded. You may deviate from the maintenance strategy suggestion from the RCM decision tree if for example the efficacy, cost-effectiveness or feasibility of the maintenance strategy are questionable. It is also possible that certain regulations prescribe planned maintenance.	Mandatory

3.4.3 Task definition

The task definition determines which planned and corrective maintenance tasks are necessary for an equipment item and the scope of the task for each planned maintenance task. Planned maintenance tasks are selected for a cause of failure for equipment if the selected maintenance strategy is FFM, CBM, SM or MOD. Corrective tasks are defined only if spare parts are advised for the failure cause.

The task definition is recorded in AMST as follows:

<table>
<tr><th colspan="3">AMST screen ‘Task’</th></tr>
<tr><td>Task Id</td><td>Unique identification number, generated by AMST</td><td>n/a</td></tr>
<tr><td>Description</td><td>Task description
Note: SAP max 40 characters</td><td>Mandatory</td></tr>
<tr><td>PMID</td><td>Reference to task in CMMS / ERP

Not used</td><td>n/a</td></tr>
<tr><td>Interval</td><td>The frequency of the task, including minimum and maximum
FFM task interval - rule of thumb:
• T= MTBF x 2 x (1-A) for single equipment, no redundancy
• T= MTBF x 3 x (1-A) for redundant equipment
• If A (availability requirement of safety feature) has not been specified, the following is assumed:
▪ A = 90% with medium risk classification,
▪ A = 95% with high risk classification.
CBM task interval - rule of thumb:
• T = 0.75 x P-F where P-F is the time between the Potential failure and the Functional failure.
SM task interval - rule of thumb:
• T = 0.75 x MTBF</td><td>Mandatory</td></tr>
<tr><td>Interval Minimum
Interval Maximum</td><td>Minimum and maximum for task interval
Filled in by AMST</td><td>n/a</td></tr>
<tr><td>Status</td><td>Task status as compared to CMMS tasks:
• New: task does not yet exist in CMMS
• Retained: task does exist in CMMS, no change specified
• Modify: task does exist in CMMS, needs to be modified
• Cancel: task does exist in CMMS, but not justified by MSR</td><td>Optional</td></tr>
<tr><td>Recommended frequency</td><td>Not used</td><td>n/a</td></tr>
<tr><td>Corrective</td><td>Checked for corrective tasks, specifying spare parts</td><td>Mandatory</td></tr>
<tr><td>Responsible</td><td>Person, team or contractor responsible for executing the task</td><td>Mandatory</td></tr>
<tr><td>Basis</td><td>Not used</td><td>n/a</td></tr>
<tr><td>Remark</td><td>Outstanding questions or action items with respect to the task.</td><td>Optional</td></tr>
</table>

Task Detail - Type	Type of work, related to maintenance strategy: FFM, Functional test CBM, Condition measurement CBM, Visual inspection SM, Replacement SM, Revision SM, Cleaning MOD, Modification proposal Repair, spare part specification	Mandatory
Task Detail - Condition	Task to be scheduled when: • Equipment in operation • Equipment down (operate using redundant equipment) • System/unit/line shutdown • Turn Around	Mandatory
Task Detail – Source	Source (such as legal requirements and standards or internal (quality) requirements and standards) that gave rise to the task.	Mandatory
Task Detail – Downtime	Not used	n/a
Task Detail - New MTBF	Not used	n/a
Task Detail - Instruction	A textual reference to a work instruction	Mandatory
Task Detail - Additional costs	Not used	n/a
Task Detail – Total costs	Not used	n/a
Assigned to Failure Cause	References to causes with risk mitigated by the task Data maintained on this tab is also shown on the failure cause tab Tasks related to Failure Cause	Mandatory
Work package	Reference to the work package containing the task. Only a single work package should be used. Data to be maintained in the AMST Work package module	
Disciplines tab	Selection of professionals needed to carry out the planned maintenance task, including the number of hours required. The disciplines are used for the calculation of the task costs. The fields Discipline Costs, Description and Instruction are not used	Optional
Spare parts tab	Selection of materials needed to carry out the maintenance task. For corrective tasks: the data is used for spare part stock level optimization	Optional Mandatory
Setup tab	Not used	n/a

3.4.4 Quality assurance: Completeness and consistency check

To complete the development, the equipment analysis is subjected to a completeness and consistency check.
With regard to completeness, a check is carried out to confirm that all the fields of the analysis steps that require input as described in this best practice have been completed.
With regard to consistency, the following checks are carried out on AMST data:

Relation between tasks and causes of failure	Check whether all selected planned maintenance tasks and spare parts have been linked to at least one cause of failure.
The relation between downtime with end effect and with risk matrix selection in category ‘Loss of production’	Check whether the downtime of causes of failure correspond with the cause of failure of end effects and with the risk matrix selection in the category ‘Loss of production’.
Relation between MTBF and risk matrix selection for ‘Probability’	Check to see if the MTBF of causes of failure correspond with the risk matrix selection for ‘Probability’
Relation between risk classification and RCM decision tree	Check whether the causes of failure with an unacceptable risk classification correspond with the question ‘Critical failure?’ in the RCM decision tree.
Relation between maintenance strategy suggestion and selection	Check if the maintenance strategy suggestion from the RCM decision tree matches the maintenance strategy selection or if there is a deviation, whether a justification has been provided.
Relation between maintenance selection and planned maintenance task selection	Check whether equipment items with a maintenance strategy selection of FFM, SM or CBM have a planned maintenance task Check whether equipment items with only a maintenance strategy selection of RTF do not have planned maintenance tasks
Relation between risk classification and advice regarding spare parts	Check if the causes of failure with an acceptable risk classification correspond with the advice regarding spare parts. Spare parts can then only be recommended based on cost effectiveness.

3.4.5 Review sessions

The review takes place to discuss the developed MSR analyses with a Review Team and when necessary to correct these.

Optionally, a selection may be made from the equipment for review prior to the review. This may reduce the workload for the Review Team members, although the exchange of knowledge is reduced as a consequence.

The following equipment selection criteria may be applied for this:

- Risk classification;
- Bad actors: cost drivers or performance killers;
- Difference in outcome planned maintenance tasks / spare parts in relation to current maintenance programme; and
- The need for review by team members.

During the review, the following questions are dealt with per equipment:

- Is the function description correct and complete?
- Are the principles in the usage profile correct and complete?
- Are the preconditions for the equipment correct and complete?
- Are the failure modes and causes of failure for the equipment correct and complete?
- Is the MTBF correct per cause of failure?
- Are the effects correct per cause of failure?
- Are the risk classification and any assumptions correct per cause of failure?
- Are the principles and assumptions made during the analysis correct?
- Has the RCM decision tree been completed correctly per cause of failure?
- Have any (legally) required standards that apply to planned maintenance been included in the selection of the maintenance strategy?
- Do you agree on the selected maintenance strategy?
- Do you agree on the advice regarding spare parts?
- Is the residual risk with planned maintenance and/or spare parts acceptable?
- Do you agree on the selected planned maintenance tasks?
- Is the task description correct?
- Is the task status correct?
- Is the task type, responsible and condition correct?
- Is the task interval correct in relation to the MTBF?
- Do you agree on the selected spare parts?
- Have all (legally) required tasks been included (if applicable)?
- Are there any current planned maintenance tasks for the equipment that have not been included in the analysis?
- What are the results of any current planned maintenance tasks?
- Is it possible to extend the task interval without increasing the risk of the cause of failure?
- Are the planned maintenance tasks and spare parts cost effective?

The outcome of the Reliability Availability Maintainability (RAM) modelling (as per EnFAIT project document D9.3) is used as input for the review sessions.

A review for an analysis is complete if the following conditions have been met:

- The analysis has been conducted step by step and the results and assumptions in the analysis are correct.
- Equipment risk classifications have been approved by the Review Team.
- Maintenance strategies and advice regarding spare parts have been approved by the Review Team.
- The selected planned maintenance tasks and spare parts have been approved by the Review Team.

If the review of an analysis does not meet the above conditions, the development and review of the analysis will be repeated.

3.4.6 Approval for implementation

The following proposals from the development are submitted to the responsible team leader(s) for approval:

MSR result	Receiving process
• Changes in equipment risk classification.	MSR implementation
• Changes in asset register.	
• New or planned maintenance tasks to be adjusted, including an estimate of the required number of man hours and the associated risk reduction.	
• New advice regarding spare parts including repair level, estimate of costs for spare part and the associated risk reduction.	Implementation of advice regarding spare parts in Inventory Management.
• Proposals for modification including the associated risk reduction.	Implementation of modifications in Management of Change process.

If a proposal is rejected, the development and review of the analysis will be repeated.

3.5 Implementation

The implementation consists of the following consecutive steps: filtering tasks, grouping maintenance tasks into work packages (work orders), exporting data from AMST and loading data into the CMMS and then starting the maintenance plans for execution.

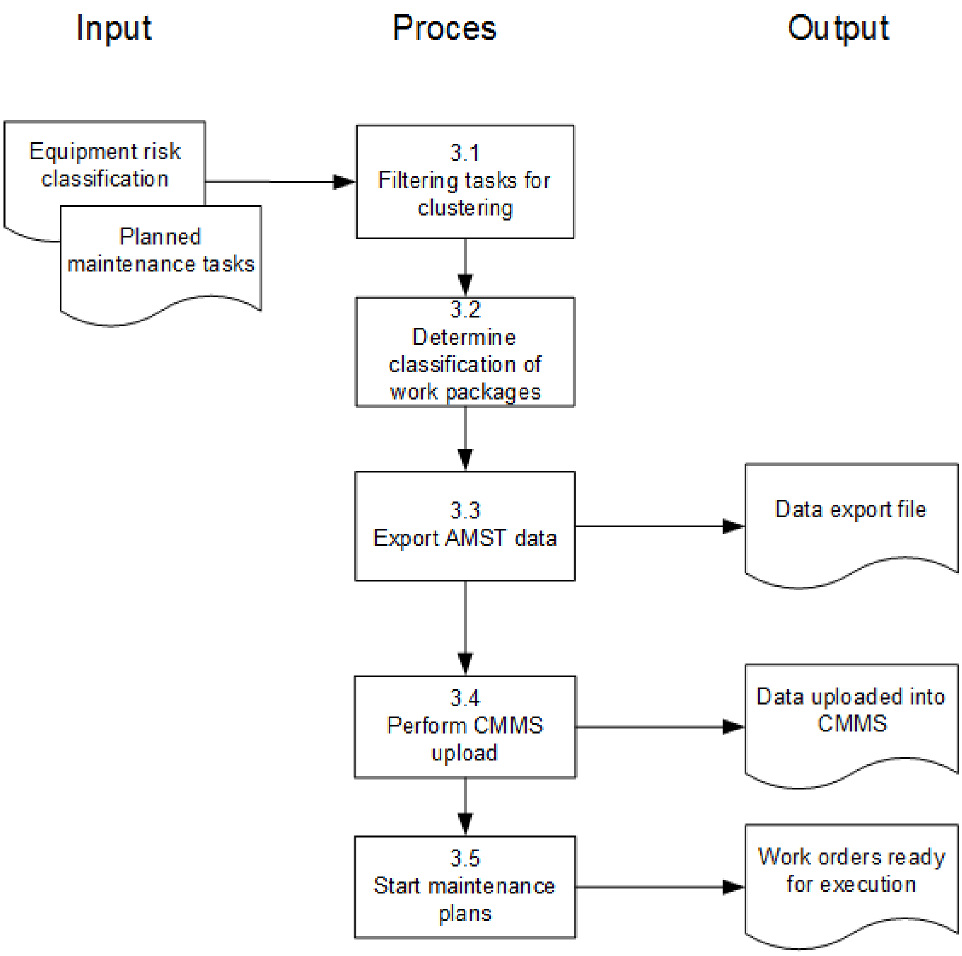


Figure 9: Flowchart MSR Implementation

3.5.1 Filtering tasks for task clustering

The following planned maintenance tasks are implemented separately:

- **Corrective tasks**
  These are used in AMST to specify spare parts, and are part of maintenance plans.
- **Modifications**
  The number of modifications tends to be limited, for each task a notification is created manually in the CMMS. This ensures that the modification can be initiated in due time.
- **One-off tasks**
  It is possible that a task only needs to be carried out once, for example in connection with guarantee conditions. These tasks are also started with a manually created entry in the CMMS.
- **Frequent tasks**

- If a task must be carried out every two weeks or more frequently, then an CMMS work order is not the right tool. This may concern daily checks or weekly greasing. Check lists are used for these tasks. An entry is created in the CMMS once a month stating when the tasks were performed. This ensures that the maintenance history remains fully available.
- **Tasks for special maintenance plans**
  Special maintenance plans in the CMMS are plans that relate to firefighting equipment, gas pipes or DCS/PLC equipment, for example. Such equipment is not directly linked to a factory or section, but is maintained for the entire site. The relevant tasks are added to the Preventive Maintenance plans in the CMMS.

Maintenance tasks in one of the above-mentioned categories are implemented in the manner indicated and are therefore not included in task clustering. The other maintenance tasks are covered in the next step.

3.5.2 Determine the classification of work packages

A work package groups tasks sharing the following characteristics:

- Maintenance is carried out for which section of the installation? It should be avoided to group tasks for different sections in the same work package.
- The equipment condition for the planned maintenance task. During a shutdown / turn-around or under normal operation?
- The task type, it should be avoided to have for example functional tests and revisions in the same work package.

Specific work packages should be created for routes, for example:

- Basic tasks executed for a large number of equipment (visual inspection manual valves)
- Condition monitoring measurements

In cases that use SAP, the PM strategy must be considered. It is recommended that all task intervals are subsumed into one single CMMS strategy. In this way, having to divide plans into tasks with for example weekly, monthly and yearly intervals is avoided. A huge number of maintenance plans means more administrative effort, which should be avoided.

After this step, a work packages report is available in AMST. This report contains the work packages with tasks and equipment. This report is reviewed by the team leaders.

3.5.3 Export AMST data

The data of equipment and maintenance tasks are exported from AMST as Excel sheets for the following CMMS data:

- Functional locations end equipment with an ABCD criticality ranking;
- Work packages with all task data;
- Spares per equipment.

This export is carried out automatically with a data export tool.

3.5.4 Perform the CMMS upload

In case the CMMS does not have maintenance plans for the assets in scope for the MSR – or is not yet configured – work packages with all tasks and equipment will be loaded into the CMMS by means of Excel load sheets, created in the previous step.

The data in the upload sheets are loaded in the CMMS.

3.5.5 Start the maintenance plans

The maintenance plans are started as soon as complete and correct data is present in the CMMS.

The start of the maintenance plans takes into account the intervals of the tasks and the date on which the last maintenance was performed. Depending on this information, the start date of the maintenance plan is established.

3.6 Completion

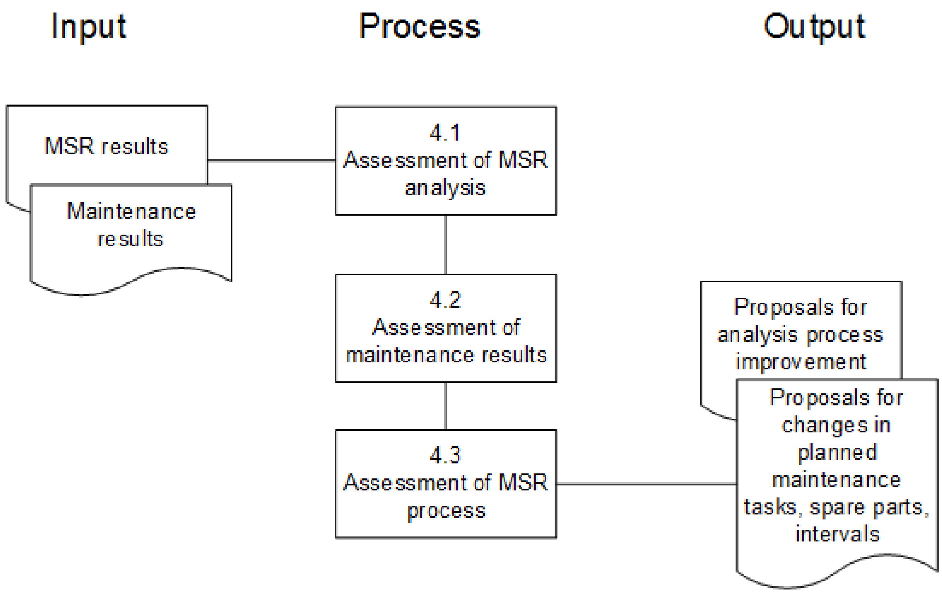


Figure 10: Flowchart MSR Completion

3.6.1 Assessment of results

Through a presentation to the MT, and subsequently to the Review Team, feedback is given about the development, review and implementation of the cluster.

Assessment of the MSR results in the short term in the form of:

- Changes in planned maintenance tasks based on:
  - Planned maintenance tasks or spare parts that have been added or amended.
  - Planned maintenance tasks or spare parts that have been discontinued.

- Modification proposals.
- Exchange of knowledge between the members of the Review Team.

Assessment of the MSR results in the long term in the form of:

- Changes in corrective maintenance costs based on the equipment risk reduction. The risk reduction is based on an inventory of equipment with unacceptable risks which were not, or not sufficiently, covered by the original planned maintenance tasks and spare parts.

Assessment of the execution of MSR in the long term in the form of:

- Assessment of the performance by the Review Team.
- Lessons learned.
- Recommendations

3.7 Analysis template management

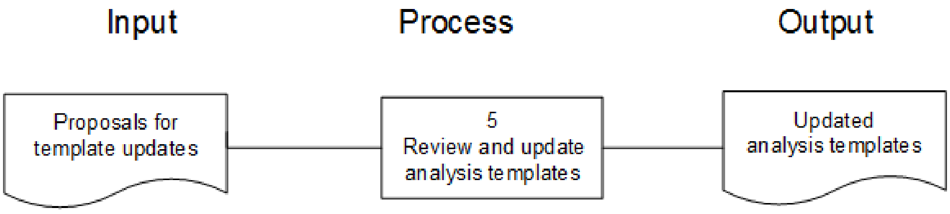


Figure 11: Flowchart MSR Analysis template management

For each equipment type, the following data are recorded in an analysis template:

- Function, '???' is entered for process specific values;
- Failure mode including code;
- Cause of failure including code;
- MTBF including source in MTBF comment;
- Local effect;
- Downtime; the principle being 100% loss of production;
- RCM decision tree; the principle being that the cause of failure is critical and not hidden;
- Advice regarding spare parts, the principle being that the cause of failure is critical;
- Task description with a maximum of 40 characters; if necessary multiple options to choose from;
- Task interval;
- Task type
- Task responsible;
- Description of spare part.

The Reliability & Maintenance Engineer makes an inventory of the proposals for changes in or additions to the analysis template.
Depending on the need, but at least twice a year, a review of the proposals will be conducted by the Reliability & Maintenance Engineer and all Maintenance Engineers involved.
Responsibility and authority to change an analysis template is vested with the Reliability & Maintenance Engineer.

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