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Ageing management methodologies and possible improvements

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Introduction

In the current economic context, it is necessary for each sector and type of structure to develop an operational, reliable and cheap method to evaluate the structure status, assess safety and trigger maintenance actions. Methods may vary between industrial sectors but methodological bridges are possible.

The current state of industrial installations and infrastructures is often not properly assessed because of the complexity of categorising and recording equipment which was overdue for maintenance or found to be defective. In order to obtain the data from which an evaluation can be made, monitoring, inspection, testing and trend analysis are required

The purpose of this Deliverable is to provide a panorama of the practices of ageing management (risk assessment, condition assessment, classification/risk/reliability-based methodologies) for various sectors (energy, oil and gas, infrastructure, etc.) and identify the best methodologies, principles and references available or under development.

The synthesis provided here is based on previous work from "Institut de la Maitrise des Risques", [IMDR], "Institut national de l'environnement industriel et des risques" [INERIS], Health & Safety Executive [HSE]. The analysis and proposal for improvement are issued from the workshop on ageing methodologies that took place in Vienna on 2nd September 2014.

1 General consideration about ageing management

1.1 Ageing management process

Operators and stakeholders are faced with a major challenge to assess the ageing structures. Different methodologies have been developed for ageing management, which are integrated into the risk assessment of a facility or infrastructure. As an introduction to the process of ageing management, some general considerations are proposed.

Ageing management implies different steps:

- **Identification** of components and degradation; it is important to identify the elements and organise them into a hierarchy;
- **Condition assessment** depending on the state of the structure and the potential failure modes (probability and consequences);
- **Decisions** after introduction of the results in a decision model; risk assessment takes different options and acceptability thresholds into account. Actions (inspection or repairs) are defined for ageing management.

The following table provides a simple comparison between the two visions.

Approach to ageing	**Statistically-based**	**Physically-based**
Ageing appearance rate	Relatively quick, sometimes catalectic	Quick, an ongoing phenomenon
Modelling	Statistic (searching for a service life rule from an observed failure sample)	- Physical, if knowledge is sufficient, where the single degradation mechanism is known - Statistical, from degradation data observed at more or less regular time intervals - Stochastic, for the treatment of uncertainties (material, loadings, degradation, etc.)
Main data	Failures (loss of function)	Degradation (e.g. inspection data, wear depth data, etc.)

The choice of approach depends on the knowledge of the ageing phenomena for each structure.

From the point of view of managing ageing, a distinction will be made between:

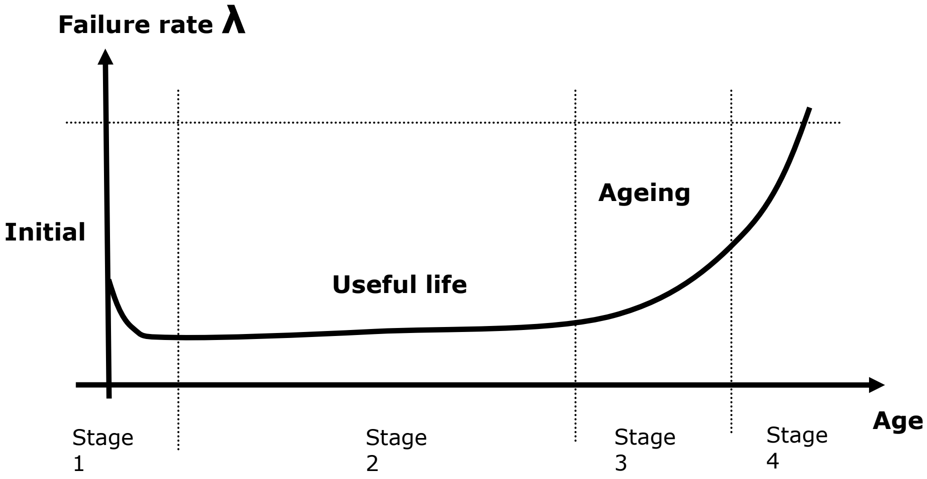
- The structures or components that will follow preventive maintenance programmes so as to retain a relatively constant failure rate. In this case, any end of service life is generally accidental and sudden. This equipment is more often classified in the **active equipment** category and covered by a statistic approach, the so-called **reliability based approach to ageing**.

- Equipment and structure that will age naturally and degrade more or less quickly depending on the dominant physical phenomena affecting them. These are inspected or monitored regularly. This equipment is generally classed in the **so-called passive** equipment category and is covered by a **physical approach to ageing**. This is the approach shared by civilian structures and passive equipment in the industry.

It is important to note that an analysis of these two visions of ageing requires learning from experience. Learning from experience therefore appears to be an unavoidable strategic element when it comes to managing industrial installation ageing. The following is mainly focused on the management of physical ageing. Nevertheless, some concepts of reliability-centered maintenance are described.

1.1.1 Statistical (reliability-based) vision of ageing

An equipment's service life, from service introduction to scrapping, generally comprises three main phases that are characterised by a random function and specific failure rates, as presented in the following figure. This illustration is usually referred to as a "bathtub curve".



- An initial period (Stage 1) results in a failure rate that decreases with operating time or the number of actions. During this period, the most fragile equipment or any equipment with flaws will be eliminated. This is the "burning in" period for electronic equipment or the "running in" period for mechanical equipment.
- A technical maturity period (Stage 2), the so-called "useful life" characterised by a constant failure rate where failure is random, accidental and sudden. This is the normal equipment-operating period and should be designed in such a way that this period should exceed or at least equal the duration of the mission assigned to the equipment.
- Lastly, a third so-called ageing period (Stages 3 and 4), during which the equipment failure rate will rise over time or is based on the number used.

A useful ageing indicator is therefore the observation of the rise in the failure rate. Two parameters will then be important for characterising ageing: the moment when the ageing appears and the way it performs once it has appeared.

Knowledge of the first parameter (the moment of appearance) will allow for the optimisation of preventive maintenance, while the second parameter (the way it performs) will allow for the evaluation of the rate at which the change of failure increases once ageing has started.

The methodology for active or simple components is therefore maintained preventively or periodically refurbished without an extensive modelling approach. Learning from experience with the equipment makes it possible to confirm preventive maintenance programmes or, on the contrary, periodically adapt them in line with the statistics on failure. Design modifications, maintenance modification (relating to preventive or conditional maintenance), renovation, replacement of defective parts or even all of the equipment, correspond to cures to ageing.

Periodic tests, or inspection while in service or simply monitoring equipment reliability parameters make it possible to highlight any start in ageing and provide help in determining when to apply these remedies.

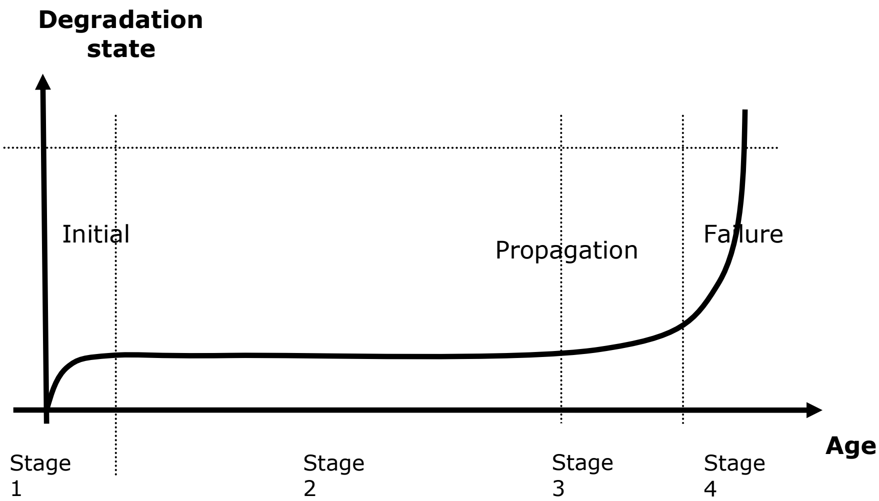
This approach is not adapted to critical and complex structures or the structure where degradation is not well-known (poor statistics or individual type of structure).

1.1.2 Physical vision of ageing

The physical approach to ageing relates especially to passive equipment (structures, piping, pressure vessels, storage tanks, etc.) or "structural" sub-components of active components (e.g. a motor stator). The ageing process is linked to a component material degradation mechanism.

In this approach, the aim is to stop any degradation triggered from causing a failure and stopping the equipment from fulfilling its mission: for example, the corrosion mechanism that causes a straight-through crack that may cause a major leak or, more seriously, sudden equipment failure.

Once the degradation has been observed, it will be monitored and all that will then be required is to act preventively (repairs, changes, etc.) to avoid a complete failure.



The challenge in this situation relates to the optimisation of conditional maintenance or in service inspections. These actions should enable the preventive detection of the start of any deterioration that has been initiated by a degradation process, as well as its propagation before failure, as shown in the diagram above

The table below presents the type of inspection linked to the various phases of equipment degradation evolution.

Degradation evolution	**Related inspection/monitoring**
Initial phase (for new equipment only)	Post-commissioning (validating equipment condition on receipt)
Priming	Inspection based on criticality
Propagation	Deterministic monitoring or repair
Failure is highly probable	Continuous monitoring or repair

Identifying the degradation mechanism involved requires an advanced knowledge of physical phenomena. A physical or statistical knowledge of the degradation linked to this mechanism is required to determine its initiation and propagation processes and detect and anticipate its evolution: This is partially the scope of structural reliability.

Managing this kind of ageing therefore requires the check of failures that integrates an inspection and monitoring method. Checks can be based on criticality criteria or defined in a regulation way. In the former case, optimisation is performed by targeting inspection actions on equipment that shows the greatest risks (major seriousness in the event of failure and/or a high occurrence probability).

1.2 SAFELIFE-X vision of ageing management

During the workshop held on 2nd September 2014, the Safelife X experts defined a global scheme for ageing management that is represented below :

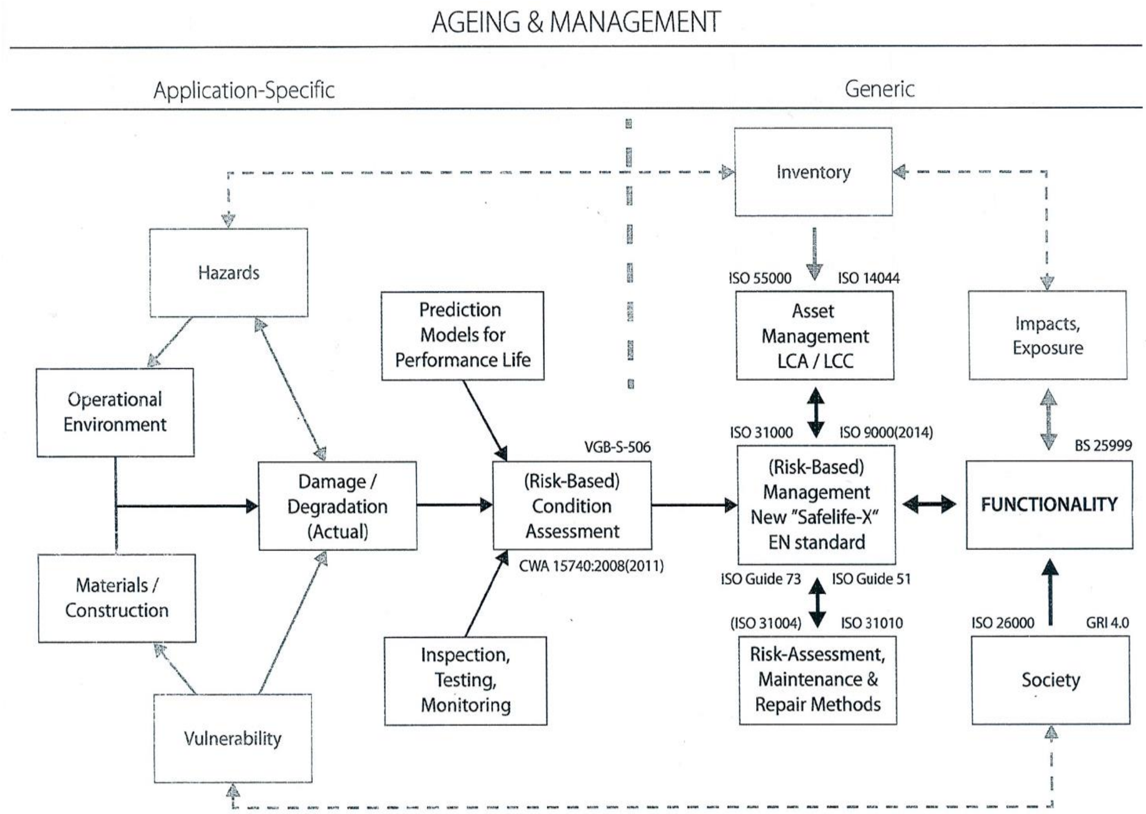


Figure 1: Ageing management process and standards

As is shown in the diagram, ageing management is mainly influenced by:

- Functionality of the equipment/structure
- Condition assessment (knowledge of the structure actual state, remaining life, etc.)
- Risk assessment, maintenance and repairs (consequences of the rupture, modification of the structure/conditions, etc.)
- Asset management (global policy and cost optimisation strategies)

The purpose of this chapter is to present briefly the main methodologies used for ageing management and discuss the possible innovations and research communalities for various sectors. The present document mainly focuses on risk assessment, condition assessment and management methodologies.

2 Risk assessment as part of ageing management

As referred to in ISO/ CEI 31010:2009, "*risk management includes the application of logical and systematic methods for:*

- *Communicating and consulting throughout this process;*
- *Establishing the context for identifying, analysing, evaluating, treating risk associated with any activity, process, function or product;*
- *Monitoring and reviewing risks;*
- *Reporting and recording the results appropriately*".

Ageing management is an iterative process aimed at identifying, analysing and reducing risk at an acceptable level.

Risk assessment is a key step of ageing management which provides a **structured process**:

- To **identify** risk; this step implies answering the following questions: what may happen, what are the causes and the potential consequences, what barriers exist to prevent or limit consequences?
- To **analyse** risk in term of **causes**, **consequences and their probabilities,** taking into account the presence (or not) and the effectiveness of any existing controls. The consequences and their probabilities are then combined to determine a **level of risk**;
- To **evaluate** risk by **comparing estimated levels of risk with risk criteria** defined when the context was established, in order to determine the significance of the level and type of risk: it may be regarded as intolerable ("red zone"), acceptable on conditions ("orange zone" where improvement may be studied) and negligible ("green zone" where no further risk treatment measures are needed).

This provides input to decisions about risk management (choosing between options with different risks, prioritising risk treatment options, etc.). Decisions may include:

- Whether a risk needs treatment;
- Priorities for treatment;
- Whether an activity should be undertaken;
- Whether several options should be followed.

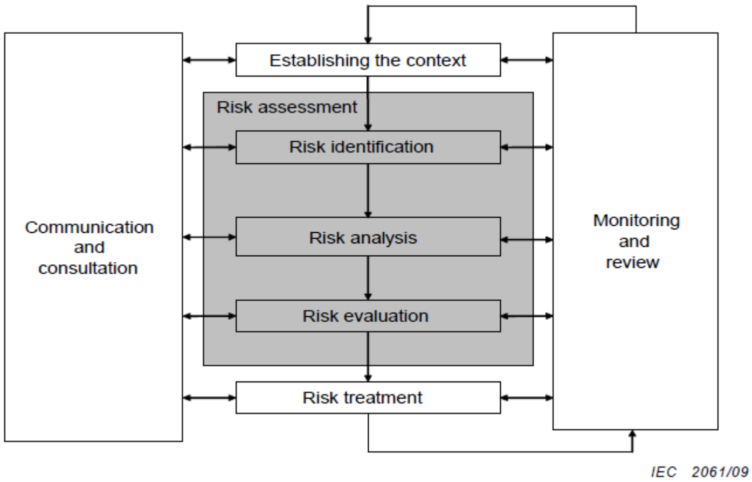


Figure 2– Contribution of risk assessment to the risk management process[0]

Risks can be assessed at an organisational level, departmental level, for projects, individual activities or specific risks. Different tools and techniques may be appropriate in different contexts.

Risk assessment can be applied at all stages of the life cycle and is usually applied many times with different levels of detail to assist in the decisions that need to be made at each phase.

2.1 Overview of risk assessment techniques

This chapter describes the current risk assessment techniques that may be divided into two categories:

- **Deductive techniques,** in which the consequences of an event are derived with certainty
- **Inductive techniques,** in which the plausible causes of an event are inferred

In these techniques, a structured set of questions is raised during **a meeting gathering a team of experts**. The structure depends on the selected technique.

To achieve a given aim, various supporting techniques can be used to improve the accuracy and completeness in risk. **For instance, preliminary analysis** may be used first to screen risks in order to identify the most significant risks (i.e. ageing risk), or exclude less significant or minor risks from further analysis. Selection is based on formerly-defined criteria. **Detailed risk analysis** may be used after a first screening to analyse risk (probability and consequence) and compare it to a target risk (acceptability of risk).

Methods used in analysing risks can be **qualitative, semi-quantitative or quantitative**. The degree of detail required will depend upon the particular application, the availability of reliable data and the decision-making needs of the organisation.

- **Qualitative assessment** defines consequence, probability and level of risk by significance levels such as "high", "medium" and "low"; it may combine consequence and probability, and evaluates the resultant level of risk against qualitative criteria.
- **Semi-quantitative methods** use numerical rating scales for consequence and probability and combine them to produce a level of risk using a formula. Scales may be linear or logarithmic, or have some other relationship; formulae used can also vary.
- **Quantitative analysis** estimates practical values for consequences and their probabilities, and produces values of the level of risk in specific units defined when developing the context. Full quantitative analysis may be implemented.

The choice of the technique depends on:

- The **objectives of the study** and **the needs of decision-makers**;
- The **available data and resources** (human and technical);
- **Uncertainty** in the data and information available **and sensitivity** of the different parameters;
- **The complexity of the application** (complex systems which need to have their risks assessed across the system rather than treating each component separately and ignoring interactions, potential implications between activities or systems, risk dependencies, etc).

It may be influenced by **the need to update** the risk assessment or **any regulatory and contractual requirements**.

The following table, from IEC/CEI 31010:2009, synthesises the applicability of risk techniques according to the expected risk process and the relevance of influencing factors.

	Risk assessment process					Relevance of influencing factors			Quantitative output
	Risk identification	Risk analysis			Risk evaluation				
		Consequence	Probability	Level of risk		means	uncertainty	complexity	
LOOK-UP METHODS									
Check-lists	SA	NA	NA	NA	NA	low	low	low	No
Preliminary hazard analysis (PHA)	SA	NA	NA	NA	NA	low	high	medium	No
SUPPORTING METHODS									
Brainstorming	SA	NA	NA	NA	NA	low	low	low	No
Structured or semi-structured interviews	SA	NA	NA	NA	NA	low	low	low	No
Delphi	SA	NA	NA	NA	NA	medium	medium	medium	No
Structure “what-if?” (SWIFT)	SA	SA	SA	SA	SA	medium	medium	any	No
Human reliability analysis	SA	SA	SA	SA	A	medium	medium	medium	Yes
SCENARIO ANALYSIS									
Root cause analysis	NA	SA	SA	SA	SA	medium	low	medium	No
Scenario analysis	SA	SA	A	A	A	medium	high	medium	No
Environmental risk assessment (toxicological risk assessment)	SA	SA	SA	SA	SA	high	high	medium	Yes
Business impact analysis	A	SA	A	A	A	medium	medium	medium	No
Fault tree analysis	A	NA	SA	A	A	high	high	medium	Yes
Event tree analysis	A	SA	A	A	NA	medium	medium	medium	Yes
Cause and consequence analysis	A	SA	SA	SA	A	high	medium	high	Yes
Cause-and-effect analysis	SA	SA	NA	NA	NA	low	low	medium	No
FUNCTION ANALYSIS									
Failure mode effect analysis (FMEA and FMECA)	SA	SA	SA	SA	SA	medium	medium	medium	Yes
Reliability Centred Maintenance	SA	SA	SA	SA	SA	medium	medium	medium	Yes
Sneak circuit analysis	A	NA	NA	NA	NA	medium	medium	medium	No

Hazard and operability studies (HAZOP)	SA	SA	A	A	A	medium	high	high	No
Hazard Analysis and Critical Control Points (HACCP)	SA	SA	NA	NA	SA	medium	medium	medium	No
CONTROLS ASSESSMENT									
Layer protection analysis (LOPA)	A	SA	A	A	NA	medium	medium	medium	Yes
Bow tie analysis	NA	A	SA	SA	A	medium	high	medium	Yes
STATISTICAL METHODS									
Markov analysis	A	SA	NA	NA	NA	high	low	high	Yes
Monte-Carlo simulation	NA	NA	NA	NA	SA	high	low	high	Yes
Bayesian statistics and Bayes Nets	NA	SA	NA	NA	SA	high	low	high	Yes

Where SA = Strongly applicable / A = Applicable / NA = Not applicable

Table 1– Applicability of tools used for risk assessment[0]

All the techniques listed in the previous table are described in the standard ISO/CEI 31010.

Some of the most classical methods are briefly presented below as an example of risk assessment methodologies for ageing.

One of them is specific to maintenance and aims at defining maintenance actions such as condition monitoring, scheduled restoration or replacement, failure-finding or non-preventive maintenance. Other possible actions that can result from the analysis may include redesign, changes to operating or maintenance procedures or additional training. Task intervals and required resources are then identified. This technique is the **Reliability Centred Maintenance** (RCM). It is based on the application of other techniques commonly used for other targets.

2.1.1 RISK ASSESSMENT FOR IDENTIFICATION: EXAMPLE OF THE PRELIMINARY HAZARD ANALYSIS

This technique is commonly used. Its objective is to identify the hazards and hazardous situations and events that can affect targets. It can be used as the starting method to identify hazardous equipment or structures that should be concerned by ageing management.

It starts with the identification of hazardous elements like hazardous substances or equipment or process. The inductive structured technique aims at identifying the consequences and causes of a hazardous event and the measures to prevent or mitigate the consequences. Additional measures can be proposed by the team of experts in risk that does not appear negligible.

The technique is relevant for:

- A new project at a design step before the precise definition of the project;
- A complex installation as a first step of screening;
- A simple installation in which the objectives of the risk do not require detailed analysis.

This technique does not require detailed information and is useful to screen the risk as a first step of a risk assessment. Preliminary hazard analysis is quantitative or semi-quantitative. Risk evaluation is not systematic and can be performed only for the selected scenarios through the use of another risk assessment technique.

This methodology can be used for the early identification of structures and equipment that need specific attention because of the critical scenarios that could occur after their failure.

2.1.2 Risk assessment for scenario identification: example of the Fault tree analysis (FTA) and Event tree Analysis (ETA)

2.1.2.1 Fault tree analysis

Fault tree analysis is a deductive technique for identifying and analysing factors that can contribute to a specified undesired event (called the "top event"). It starts with the identification of the top event. It is largely used in any industrial sector (aeronautic, nuclear, chemical industries, etc).

The causes of all forms (technical or human) are identified in a deductive way and depicted on diagrams describing the relationships between them. Prevention measures are identified.

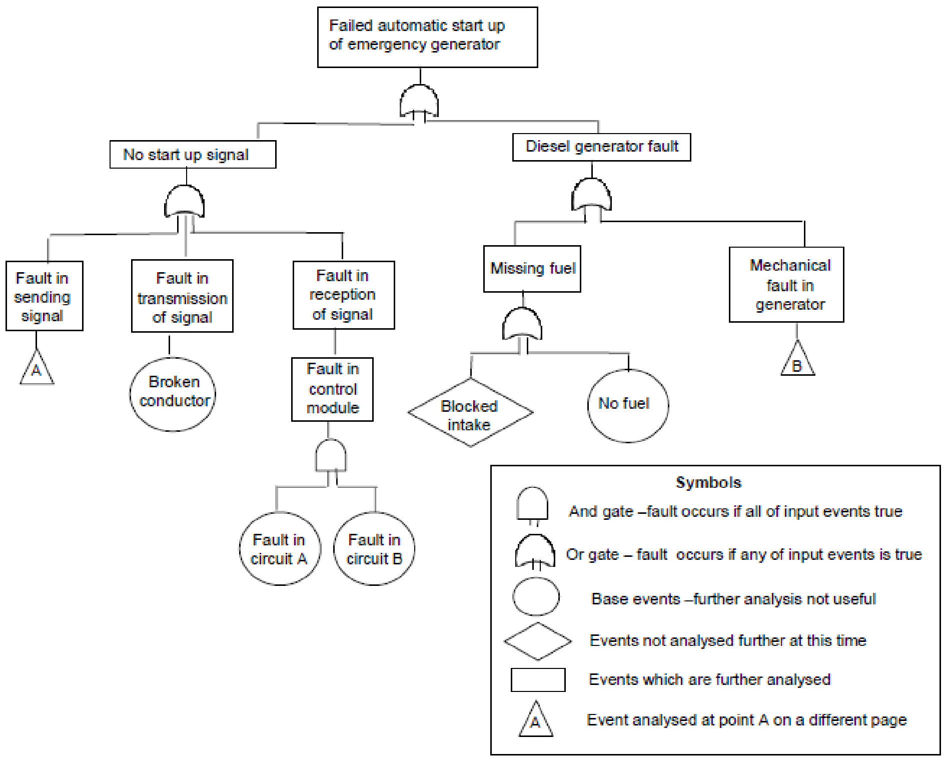


Figure 3: Example of an FTA from IEC 60300[0]

FTA can be qualitative, semi-quantitative or quantitative. It aims at evaluating the probability of the top-event. Except for simple fault trees, if quantitative probability is calculated, a software package is needed to properly handle the calculations when repeated events are present at several places in the fault tree, and to calculate minimal cut sets.

FTA can follow other techniques such as Preliminary hazard analysis (PHA), Failure Mode Effect Analysis (FMEA), Hazard and operability studies (HAZOP), etc.

It enables interactions between causes to be given and identifies minimal cuts.

It requires a large number of data and knowledge about the system. Nevertheless, human factors or domino effects are not assessed precisely. And causes are often binary (fail or not fail).

This methodology can be used to identify the root causes of the failure and the interaction of a physical failure with other systems. FTA can be applied to simple systems, but is not well adapted to very complex systems.

2.1.2.2 Event tree analysis (ETA)

FTA is an inductive methodology that starts with a more or less detailed splitting of the system. To the contrary of FTA, the starting point for the ETA is an external event or a hazard applied to the system. The objective of the methodology is to identify the consequences of an event and usually includes the analysis of the mitigation measures. It is widely applicable to all forms of systems. The consequences and the actions of mitigation measures are depicted in diagrams.

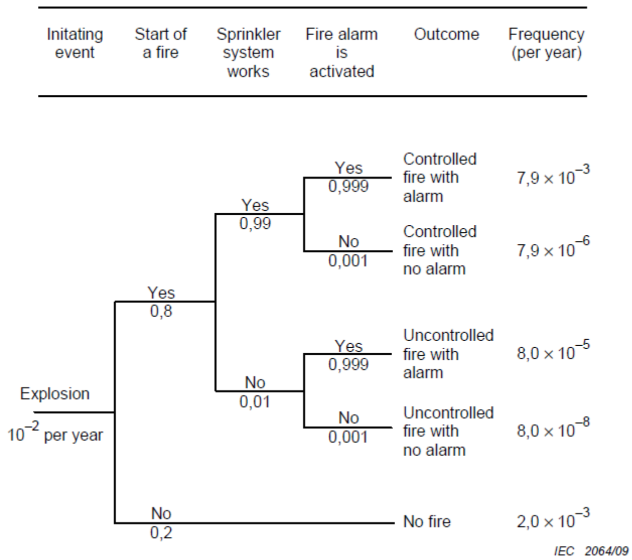


Figure 4: example of an event tree[0]

ETA is a graphical technique and can be qualitative, semi-quantitative or quantitative.

During the ageing evaluation process, these methodologies can be used for the identification of failure scenarios due to an ageing degradation and involving critical consequences.

2.1.3 Risk assessment for condition assessment: Failure mode effect analysis (FMEA and FMECA)

The Failure Mode Effect Analysis (FMEA) is an inductive technique that aims at analysing failures of materials or components and identifying their causes and consequences. This technique is used to identify the ways in which the components, systems or processes can fail to fulfil their design intent. In case of the analysis of criticality, the method is called FMECA.

The technique starts with the splitting of the system into different sub-systems. Their functions are identified.

Failure modes (to fail or perform the function correctly) are given through the use of guiding words relating to the general behaviour (start, stop, delayed work, loss of input, etc.). They are commonly used to analyse systems of different technologies (electrical, mechanical, etc.) or that mix technologies.

FMEA can be applied to the global system or to components. In the latter case, it requires a fine splitting of the system, which may require important means in the case of a complex system.

It is useful to determine the common failure modes that can have consequences on several components of a system. This involves the identifications of the measures to prevent or mitigate the effects.

This criticality analysis (in case of FMECA) is usually qualitative or semi-quantitative, but may be quantified using actual failure rates.

For more details, IEC 60812 entitled "*Analysis techniques for system reliability – Procedure for failure mode and effect analysis (FMEA)"* can be consulted

2.1.4 Risk assessment for management: Reliability centred maintenance (RCM)

Reliability-centered Maintenance (RCM) is used in a wide range of industries. It can be implemented at any stage of the cycle life of a project (design, development phase, operation, etc.).

RCM is a **risk-based methodology** to identify the maintenance policies that should be implemented to manage failures. It takes into account the degradation mechanism responsible for the failure.

- **Risk identification** consists of the identification of functions and the events that may induce a loss of these functions. Maintenance tasks that may prevent the loss of functions or reduce their effects are identified. The consequence may be related to safety (personnel and/or environment) or the economy (for instant, the loss of production).
- **Risk analysis** consists of estimating the frequency of each failure with or without maintenance being carried out. The consequences are established by defining failure effects. A risk matrix that combines failure frequency and consequences allows categories for levels of risk to be established.
- **Risk evaluation** is then performed by selecting the appropriate failure management policy for each failure mode.

RCM require a good knowledge of the equipment and structure, as well as the failure modes of the different components.

The basic steps of an RCM programme are as follows:

- Initiation and planning (identification of the data available, the competencies and needs of training, the contexts of operation)
- Functional failure analysis (definition of the functions, their failures and modes of failures, effects and risk); an FMECA gives structural support to that step
- Task selection (assessment of the consequences, choice of maintenance tasks, definition of intervals between actions)
- Implementation (detailed identification of the maintenance tasks and rationalisation of the periodicity of the tasks, assessment of the consequence of ageing)
- Continuous improvement (control of the efficiency of the maintenance, control that expected targets (safety, economic and operational) are met, assessment of the effect of ageing)

RCM requires rather important means. For more details, IEC 60300-3-11, Dependability management – Part 3-11: Application guide – Reliability centered maintenance can be consulted.

2.2 Representing outputs of risk analysis

Risk analysis provides information about the risk defined by the probability and consequence of events. This analysis may be qualitative, semi-quantitative or quantitative. According to the objectives and outputs of risk analysis, different tools can be used to evaluate risk and compare the level of risk with a previously defined acceptable risk. The main tools are:

- <u>FN curves:</u> these curves represent the frequency of an event and the number of fatalities corresponding to the event. They are used to define the tolerable/acceptable risk. An example is given below:

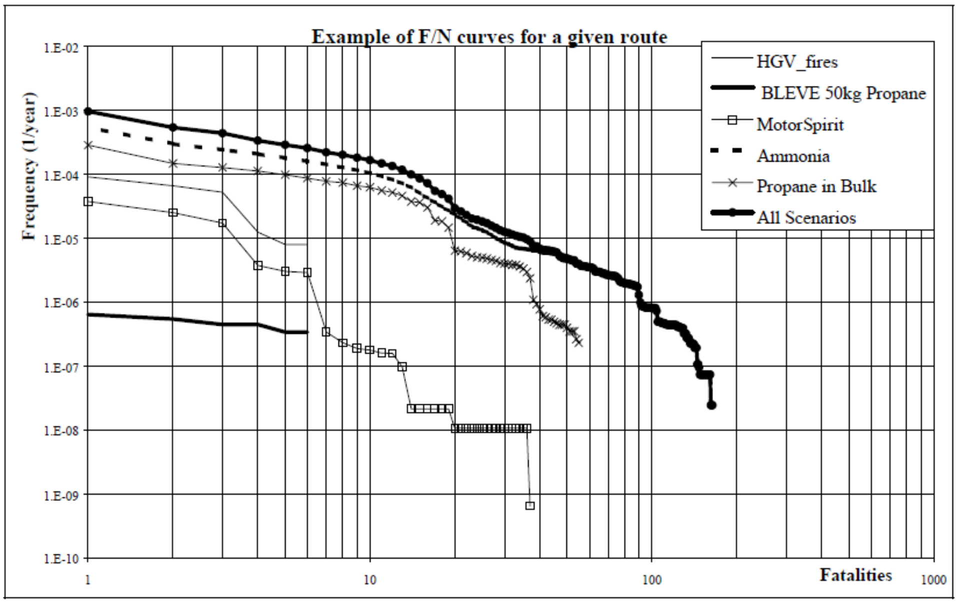


Figure 5: FN curve example for dangerous transportation on road [BOUISSOU]

- Risk matrix: this is the most typical way to represent risk as a combination of probability and consequences. An example is given below from [API581]

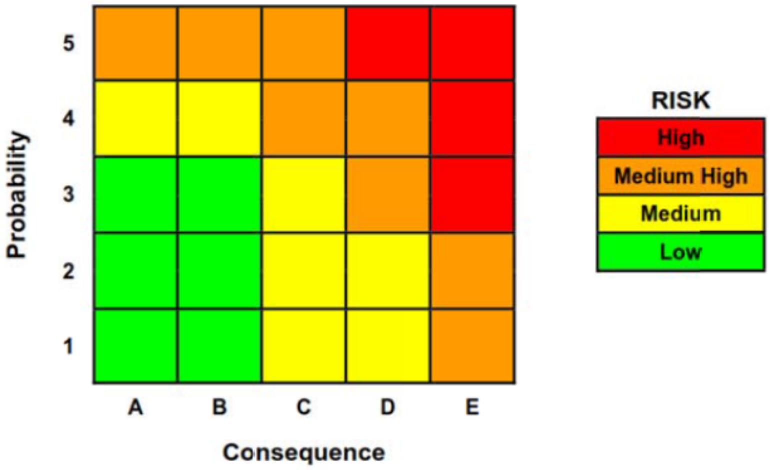


Figure 6: risk matrix for risk-based inspection [API581]

- Risk indices: these indices can be based on probability, intensity and consequences (i.e. number of injuries). They can be both qualitative and quantitative.

Results considered as decision tools also include cost/benefit analysis, multi-criteria decision analysis (MCDA) or decision trees.

3 Condition assessment as part of ageing management

To manage ageing, the state of the structure has to be estimated:

- Firstly, a **diagnosis** of the structure aims to assess its **current state of safety**; this step includes:
  - Knowledge of the structure, including its precise state, historical background, environment; ideally, this should be in the form of a systemic description of the structure and its environment, including the stakeholders, requirements, as well as the operational, functional and organic architecture all along its lifecycle
  - Assessment of the future potential development of the structure and its environment, depending on the degradation mechanisms and changing performance requirements
  - Assessment of the uncertainties of these parameters, including ageing management (inspection, monitoring, maintenance and repairs)
- A **forecast** is then performed to assess the **remaining service life**

The methodologies are based on the experience available in a database or industrial sector/field of application. This chapter gives an overview of the principle methodologies used in different fields and industries.

3.1 Types of methodologies

Methodologies for condition assessment can be implemented in different ways which imply more or less resources. The choice of the methodology may be dependent on the:

- Stage of the life cycle reached
- Knowledge of the structure
- Knowledge of the degradation mechanism

Many methodologies exist for the condition assessment of a structure or component. Some technical aspects were discussed in the Deliverable 2.2 of this Work Package 2. The purpose here is to identify the global principles of the different methodologies for structural assessment. The Structural Assessment Monitoring and Control (SAMCO) guideline proposes an interesting classification for structural assessment that is representative of existing methodologies in various sectors.

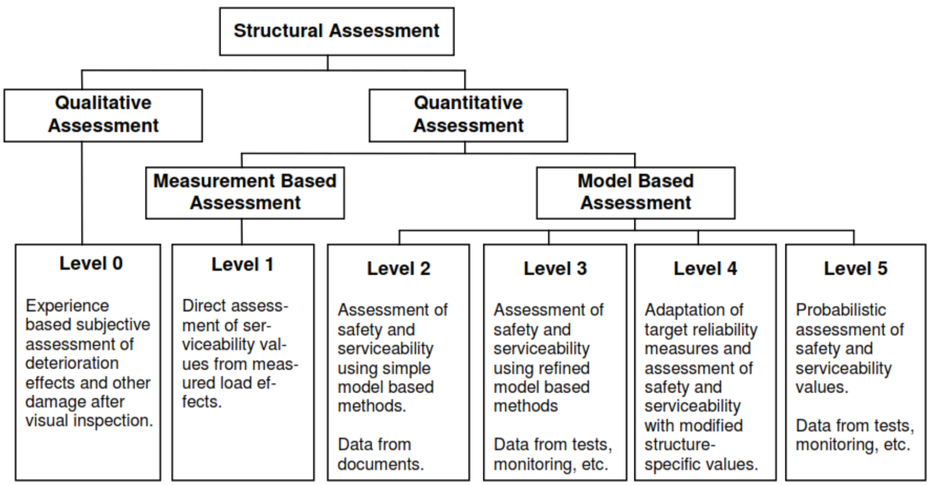


Figure 7: levels of condition assessment

The different types of condition assessment can be summarised as follow [IMDR]:

- Level 0 –the assessment is based on the experiment used for the revaluation of the structures by means of the visual observation of the degradation and signs of damage (cracking, chipping, etc). The expert provides the condition assessment and qualification for service.
- Level 1 - determination of the effects of the loading based on measurements: the qualification of the serviceability is obtained by the measurement of the indicators of the performance and their comparison with the value thresholds. There is no numerical analysis of the structure, the levels of the indicators are obtained in design codes or individually specified.
- Level 2 - method based on the analysis of documents: the qualification of the capacity of the structure and its serviceability is carried out according to information resulting from the design and documentation of the degradation. The analysis of the structure is generally carried out using simple methods. The checking of safety and the qualification for service is based on the safety coefficients.
- Level 3 - method based on additional investigations: the qualification of the capacity and serviceability are based on specific information of the site and non-destructive testing. The analysis of the structure is carried out with precise and detailed methods. The qualification is made on the basis of safety coefficient.
- Level 4 - modified reliability target: the checking of the capacity is done with safety coefficients that have been modified compared to the initial design criteria. Advanced modelling technologies are generally used to justify the new criteria. This assessment can be influenced by the modification on the structure or the loading.
- Level 5 - complete probabilistic evaluation: considering all the basic variables and their statistical properties, the qualification is carried out by an analysis of reliability of the structure instead of the partial coefficients; uncertainties are thus modelled by random variables. The threshold is then a probabilistic value for failure.

Depending on the level of methodologies, the results to assess the condition of the structure can be :

- An expert qualification of the structure
- Indicators of performance
- Quantitative value of the safety factor
- Probability of failure

The quantitative models can be combined with predictive degradation models to provide the remaining life assessment.

3.2 Choice of methodologies during life cycle

Condition assessment is important at any stage of a life cycle. However, each stage can require a different type of approach. A common view for condition assessment is to adapt the methodology to the life stage of the structure.

Based on the classical bath-tub curve, a summary of the consideration to choose the appropriate condition assessment is proposed below. The considerations are based on the Joint Committee on Structural Safety (JCSS), SAMCO and HSE.

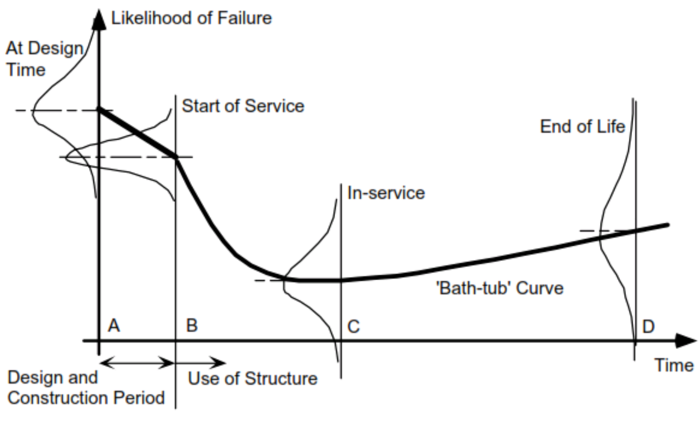


Figure 8– Bath-tub curve [JCSS]

Ageing of a structure is represented by a "bathtub" curve composed of four stages. This represents the probability or rate of failure of a population of assets over its life. The shape of the curve reflects the rate of degradation and effect of accumulated damage on operating margins.

Life cycle can be divided into four stages of ageing according to the position on the curve. HSE proposed the following denominations for the stages:

- Stage A: Initial or Design & construction ending up in Commissioning & Start-up
- Stage B: Maturity or Use of structure or facility
- Stage C: Ageing
- Stage D Terminal

The different stages imply different levels of analysis as described below:

- **Stage A - Initial:** As the equipment or structure enters service, there may be a relatively higher rate of damage accumulation and failures. This is due to installation stresses or erroneous design or faulty workmanship, but it is not ageing
- **Stage B - Maturity:** This is when the equipment is predictable, reliable and assumed to have a low and relatively stable rate of damage accumulation and few issues requiring attention. The condition assessment is generally based on level 0 to level 2 methodologies.
- **Stage C - Ageing:** By this stage, the equipment has accumulated some damage and the rate of degradation is increasing. Signs of damage and other indicators of ageing are starting to appear. At this stage, it becomes more important to determine quantitatively the extent and rate of damage and make an estimate of the remaining life time. The condition assessment at this stage is generally based on level 2 to level 4 methodologies.
- **Stage D - Terminal:** When equipment becomes severely degraded, the rate of degradation tends to increase and is not easy to predict. Repair, refurbishment, decommissioning or replacement will be needed before too long. In this final stage, a very detailed assessment of the qualification for service is needed. The methodologies used for this stage are based on level 4 to level 5 types.

4 Methodologies for ageing management

4.1 General classification

This chapter describes the existing methodologies regarding ageing management.

Operators who put into place an ageing study covering their installation have two major concerns:

- **Safety**: Ageing must not affect components that are important for safety. The actions required to manage any ageing issues must absolutely be put into place. Any ageing that may arise must be managed and corrected.
- **Loss of production or availability, maintenance, repair or replacement costs**: Component ageing must not penalise profitability. Consequently, it is important to detect components that may cause ageing, to plan for the development of this ageing and take the necessary measures and countermeasures.

Therefore, the importance of anticipating ageing can clearly be seen and its appearance anticipated so it can be managed. Anticipation refers to identifying the potentially penalising events before they happen, so as to evaluate the risks that they present and prepare and implement suitable monitoring, preventive maintenance or replacement actions.

Three main methodologies are defined:

- Classification-based methodologies (or scoring systems)
- Risk-based methodologies
- Reliability-based methodologies

All these methodologies can be quantitative or qualitative. A global scheme for the content of the methodologies is presented below, then a description of each type of methodology given.

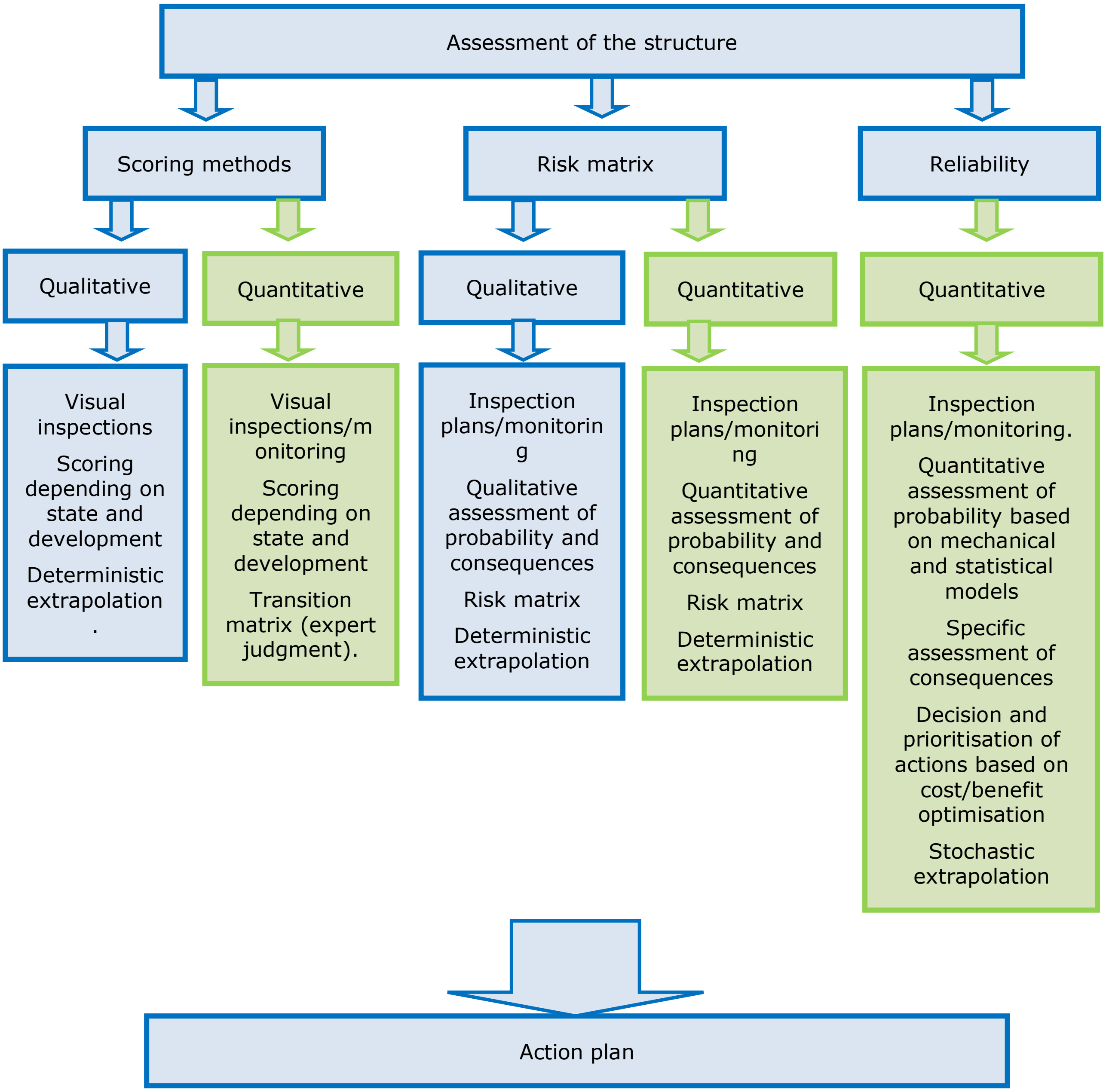


Figure 9 – Three types of methodologies for ageing management [IMDR]

4.2 Classification-based methodologies (scoring systems)

4.2.1 DESCRIPTION OF THE METHODOLOGY

The classification-based methodologies (or scoring systems) are performed for large structures with many components. For instance, civil works in industries, bridges, etc. use these methodologies.

Upstream, it is necessary to define the ageing management policy: target of rate of accidents, possible costs or benefits, definition of the service in charge of ageing management and allocation of objectives and budget.

In classification-based methodologies, the assessment of ageing is performed by scores of inspection and expertise. In this way, ageing is evaluated from the current conditions. Inspection gives information on the current state (observed disorders: nature and extent). Models of development are implicit. As such, the classification is based on the judgment of the expert.

These scores are first allocated to each component and an aggregation can made to assess the ageing of the whole structure. A general assessment of the state of the structure and its components is then possible, leading to:

- A global assessment of the structure
- Definition of the prioritisation of actions

The process for the classification-based methodologies is shown in the following figure.

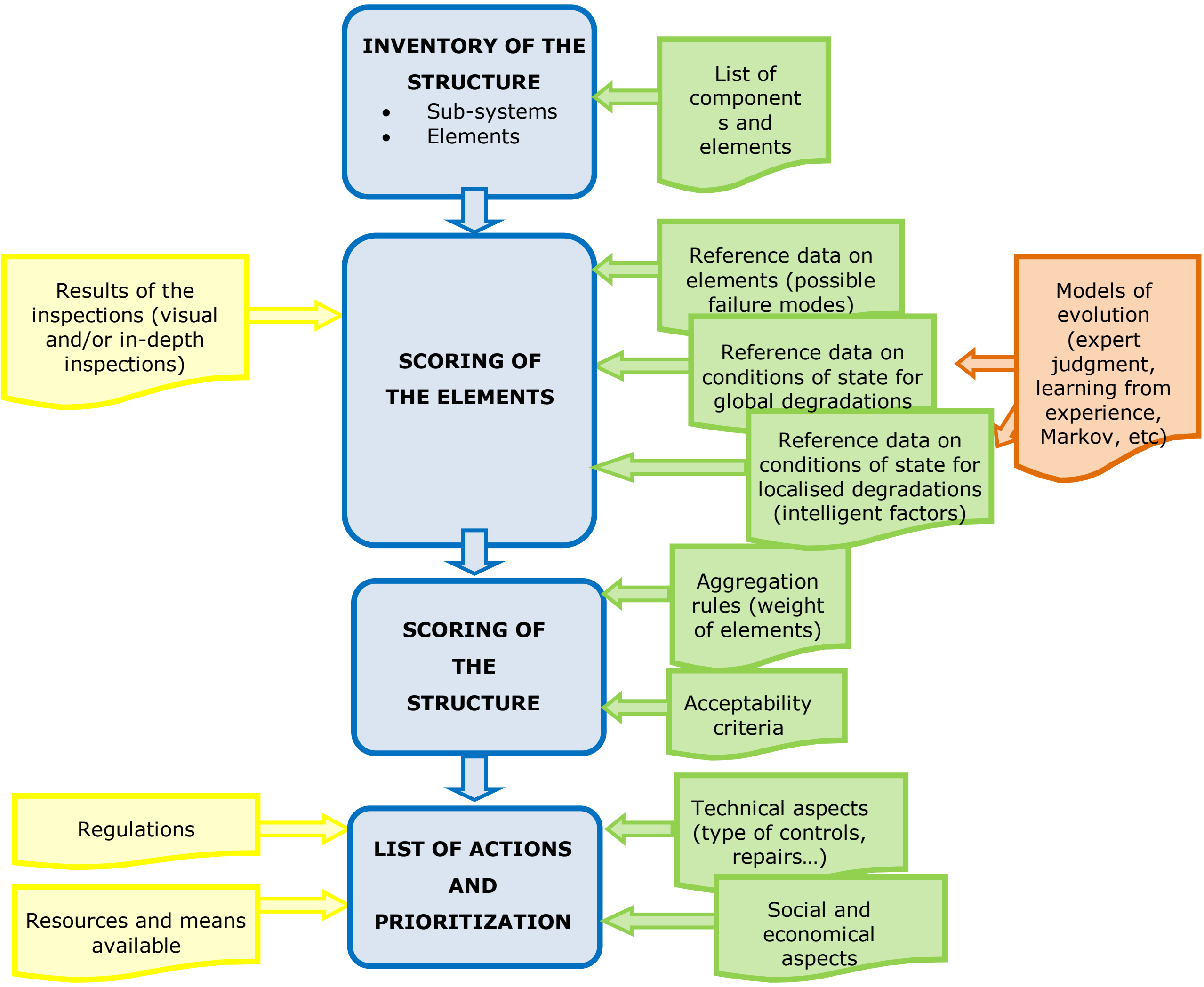


Figure 10– Process for classification-based methodologies

HSE notes that a simple scoring system would have two components:

- One relating to the current ability of the structure to ensure the required functions and
- The other relating to the possible development of an observed degradation, leading to a decrease or loss of the required functions. At this stage, there is no specific consideration as to the rate of degradation. The approach remains qualitative.

It is necessary to have a common scale for assessing scoring. Reference or specific standards to assess scores are needed to reduce subjectivity and allow consistency in the method.

Examples of this type of methodology can be found in [SETRA], [NIH], [ASSHTO] or [Hydro-quebec].

4.2.2 ADVANTAGES AND LIMITS

The classification-based methodologies are qualitative and deterministic.

These methods appear relevant for large structures with many components because of their simplicity.

The required data are:

- An inventory of the structures and decomposition of the structures in different elements
- Information about current state (observed data from inspections and visual controls)
- Information on the future conditions of the elements are implicit; reference data on conditions of state are required (professional guides)
- Qualitative acceptability criteria defining whether actions are required according to the observed state of the element

The advantages of these methodologies are:

- Simple methodologies taking into account formal experience
- The required data are limited to deterministic and regulated data; they do not require the mechanical or environmental analysis of the structure nor precise statistical data
- Classification depends on the current state, as well as the potential future state and is invariable
- Decision-making is consistent (actions to be taken depend on the classification of the structure)

The limits of these methodologies are:

- Aggregations are not always rigorous (identification and potential weight of the elements and failure modes)
- Rare scenarios may not be taken into account
- Assessment of the state of the structure may be subjective, but it can be improved by reference professional guidelines
- it is necessary to have a common scale for assessing scoring
- Uncertainties are supposed to be taken into account using a conservative approach
- No evaluation of the probabilities nor consequences that may improve decision-making
- Decision-making not based on cost optimisation
- Stakes included in decision are not always explicit (consequences in terms of safety, service, cost, etc)
- Definition of the actions (frequency and nature) not precise
- Sensibility analysis not possible
- it cannot be used for design (require information from previous inspections)

4.3 *Risk-based methodologies*

4.3.1 DESCRIPTION OF THE METHODOLOGY

The aim of this methodology is to focus ageing management on high-risk equipment to define inspections (frequency and type of controls) to reduce risk.

In risk-based methodologies, the probabilities and consequences of failure modes are assessed. Usually generic approaches are used, which feature specific data for a given industrial sector.

Risk assessment takes degradation modes and reliability of inspections into account. A remaining life is estimated, which leads to an action plan.

These methods require an important database of failure rates and influence of different factors on the development of the structure.

These methods may be qualitative, quantitative or semi-quantitative. The choice between them depends on the quality of the data and the effort to be made for assessment.

The risk-based methodologies are used for mechanical equipment in industries in a quantitative or qualitative way. They are also used for civil works in a qualitative way.

They may also be used in other sectors, but would require adaptation to assess the probabilities and consequences.

The methodologies are described in documents such as [API580/581], [EEMUA 159], [ASME 20], etc.

The SAFELIFE EN standard on Risk Based Inspection (RBI) is dedicated to set a framework for this type of approach.

The methodology is divided into several steps:

- Identification of the system
- For each component of the system, identification of the failure modes
- For each component, assessment of the risk with no inspection, including assessment of the probability of occurrence of the accident and assessment of the severity of consequences. According to the methodologies, these assessments may be qualitative, quantitative or semi-quantitative. Consequences can be financial impact, impacted surface area, environmental impact, quality of service, reliability, safety, etc.
- If the risk is high, a definition of inspections (frequency, nature) and new assessment of probability that takes inspections into account. The methodology enables inspection actions to focus on high-risk components.

Some adaptations of these methodologies have been developed:

- Risk Based Life Management (RMLN) is a method of In-Service Inspection (ISI) for equipment based on the estimated risk, which consists of focusing inspection on the higher risk components
- Risk Based In-Service Inspection (RB-ISI) is implemented in US nuclear plants for passive equipment (drums and piping); after analysis of the system, the components of the structures which have to be inspected are determined and the nature and frequencies of the inspections are defined
- Risk-Based In-Service Testing (RB-IST) is implemented in US nuclear plants for active equipment (pumps and valves); equipment is tested or subjected to preventive maintenance, in order to check it can work properly.

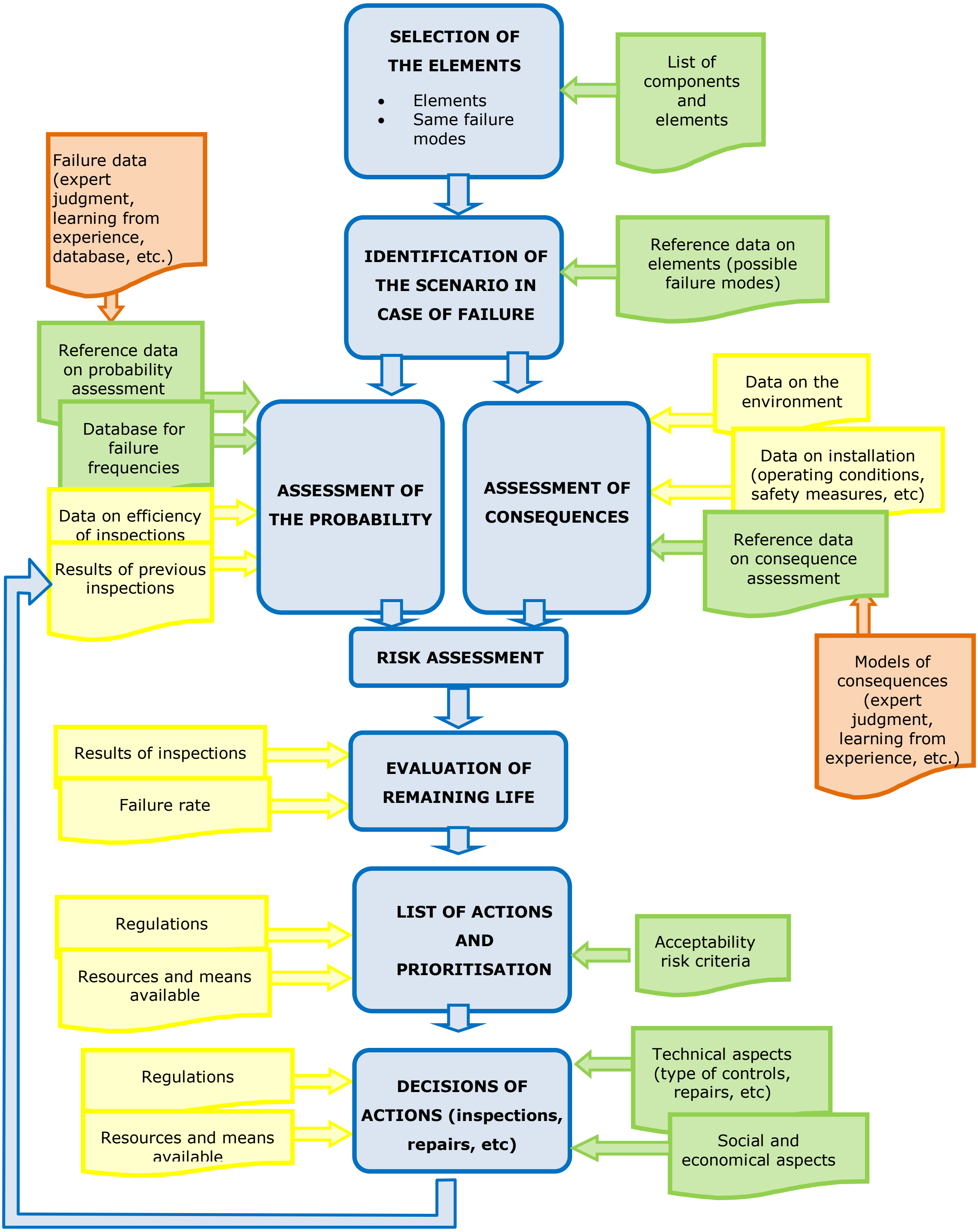


Figure 11– Process for risk-based methodologies

Some calculation codes are based on RBI methodologies: [ASME-CRTD], [API 580] and [API 581]. Examples can also be found in [EEMUA159], [HSE-2] or [IAEA].

4.3.2 ADVANTAGES AND LIMITS

This methodology requires:

- Structured organisation for ageing management
- A large amount of statistical data and knowledge on degradation
- Reference guidance for each sector

The advantages of this method are:

- Possibility to use qualitative or quantitative methodology according to the context
- Inspections and maintenance are focused on high-risk equipment; there is an optimisation of the cost of maintenance
- Standardisation of the assessment of probabilities of occurrence and consequences by capitalisation and formalisation of the data (for instance, in the chemical industry) enables consistency of the results
- Consequences can include different aspects (financial and/or impacted area)
- Consistent methodology for risk assessment and definition of inspection plans
- Does not require mechanical or environmental analysis of the structure nor precise statistical data

The disadvantages of this method are:

- Requirement of qualified persons to collect and analyze data; they must have a good knowledge of the equipment, working conditions, environment, etc. and good knowledge of the methodology
- Difficult to adapt the methodology to new industrial sectors, because it would require an adaptation for the assessment of the probabilities and consequences
- No complete optimisation of the cost of maintenance
- Uncertainties are not assessed; analysis of sensibilities is not possible
- Cannot be used for design (requires information from previous inspections)

4.4 Reliability-based methodologies

4.4.1 DESCRIPTION OF THE METHODOLOGY

Reliability-based methodologies consist of a fine analysis of the reliability of the structure, taking into account each failure mode for the current and provisional state of the structure. A mechanical model is used for the ageing of the structure. The assessment of the potential cost of lifecycle leads to an optimisation of the inspection and maintenance plan.

These methodologies are probabilistic and quantitative.

They require many statistical data on the materials and state of the structure, as well as precise behaviour models.

A failure scenario is associated to a performance function. The different parameters involved in this function are based on statistical data. The interactions between the different parameters are taken into account. The assessment of the probability of failure can be performed using both mechanical and reliabilities models.

The different steps of the reliability-based methodologies are:

- The structure is defined including its function, behaviour, operating conditions and potential failures (fault tree analysis, event tree, FMEA, etc.)
- Provisional models for mechanical behaviour, with or without defects, are built, as are probabilistic distributions of design/operational variables (statistic analyses, stochastic models, etc.)
- Potential failure scenarios are identified; the proper working of the system is defined by performance functions (or limit states) to be respected; if one of the limit states is reached, the failure occurs
- For each failure scenario, the reliability level is calculated, including sensibility factors; these factors are important for decision-making, control of quality and optimisation of the system
- As a last step, the fully quantitative probability of the failure of the system is assessed
- Cost-benefit approaches can be used to optimise inspection and maintenance plans that take cost-models (LCA/LCC), regulations, etc, into account

This type of methodology is particularly suitable for getting precise quantitative failure probability that integrates well-defined uncertainties.

This type of methodology can be complex and a global scheme cannot be reasonably proposed. For the purpose of illustrating the reliability principle, the condition assessment based on reliability analysis and a general stochastic procedure can be identified in SAMCO. This procedure can be integrated in the overall process of ageing management.

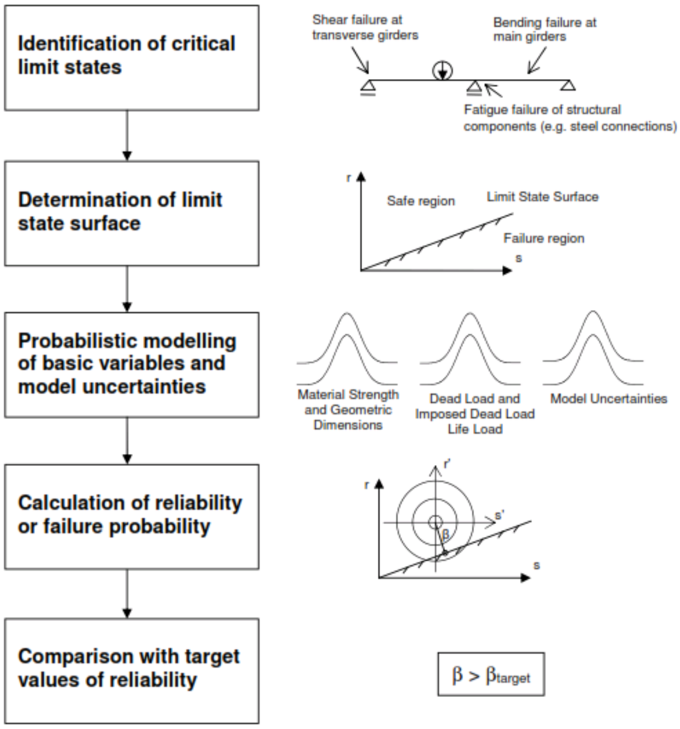


Figure 12: Structural reliability analysis process [SAMCO]

The general concept of structural reliability assessment of existing structures is described in the normative document ISO 13822. Nevertheless, the full methodology for ageing management is not standard. Examples of methodologies based on reliability can be found mostly in the civil engineering and offshore industry. Some relevant information is available in the IRIS project, [JCSS] works, [ESREDA] or [SAMCO].

4.4.2 ADVANTAGES AND LIMITS

The advantages of these methodologies are:

- Can be used in any industrial sector
- Consistent methods for risk analysis and definition of inspection plans
- Precise calculation of the probabilities and the consequences
- Possibility to take any new information from inspections, experience,, etc, into account
- Sensibility analysis and characterisation of variables of decision
- Rare events with major consequences can be considered
- Continuous assessment of the risk and global optimisation
- Risk decision process leads to an effective optimisation of the reliability management and investment plan

The limits of these methodologies are:

- Method is complex, requiring significant human and technical resources
- Requires high level of expertise for analysis and interpretation of the results
- Some data are difficult to measure
- Statistical data may not exist
- Calculations may become impossible because of too sophisticated models

5 Analysis and proceedings of workshop on ageing methodologies

5.1 Comparison and analysis of the ageing methodologies

The following conclusions can be proposed as a general point of view on the methodologies:

- Classification-based methodologies aim to make a quick selection of the critical components, depending on their state of conditions
- Reliability-based methodologies require important resources (mechanical, physical and statistical models) but enable a precise evaluation of the safety of a component
- Risk-based methodologies are a compromise between the other methodologies. Qualitative risk-based methodologies are easier to implement, but do not enable a decision based on rational argument to be taken. Quantitative methodologies can also be used and appear more consistent.

The implementation of such methodology depends on the:

- Available resources on site (to implement and maybe adapt generic methodologies)
- Available resources in the industrial sector to develop reference data and rules
- Information and means available

The following table proposes a classification of the methodology, depending on the needs, advantages and limitations of each one.

Methodology	**Classification**	**Risk-based**	**Reliability**
Required amount of data	Low	Significant	Very high
Data	Qualitative	Qualitative and quantitative	Quantitative
Time-consuming	Low	Medium	High
Modelling	None or simple	Simple to complex	Complex
Reliability	Low	Medium	Low to high (depending on data)
Qualification needed	Low (to apply) High (to indent the methodology)	Medium to high	High
Risk evaluation	Insufficient	Global view - scenario evaluation	Quantitative representation

Communication	Difficult	Very good	Very difficult
Structural field of application	Large structure with low or medium stake	Critical structure/component with significant stake	Critical component with critical stake

Table 2 – Applicability of tools used for ageing management

The following table summarises the differences between the approaches in terms of condition assessment, risk assessment and decision-making process.

NEEDS	**Classification methodologies** Qualitative approach based on aggregation of indicators from observed date. Quantitative or predictive models not used	**Risk-based methodologies** Qualitative, quantitative or semi-quantitative approaches Risk assessment Optimisation of inspection and maintenance plans according to the risk	**Reliability methods** Quantitative approach based on statistical and physical models Optimisation of inspection and maintenance plans according to the cost
Current state assessment of the structure	• Assessment based on aggregation of indicators related to the apparent state of the system	• Current state is starting point for assessment • Variable methodologies depending on the risk • Statistical approach of degradation	• Detailed assessment based on the analysis of the structure and models
Remaining life assessment from technical and economic aspects	• Not explicit • Included in the expert judgment for scoring	• Remaining life assessed • Influence factors taken into account	• Behaviour and statistical models
Risk Assessment - of the failure modes -of their probabilities -of their consequences	• Failures modes identified by expert judgment • Qualitative approach with no explicit evaluation of probability nor consequence	• Identification of failure modes based on reference guides • Assessment of probabilities and consequences • Risk matrix • Assessment can be qualitative, quantitative or semi-quantitative • Different types of consequences possible (cost, surface, death, etc)	• Failure modes identified • Fine analysis of each mode based on models • Probabilistic models with formal experience taken into account (Bayesian models) • Interactions between factors taken into account • Uncertainties modelled
Risk acceptability	• No complete risk analysis • Qualitative thresholds defining if actions have to be taken	• Risk matrix with criteria of acceptability – As Low As Reasonably Possible (ALARP) criteria; • Prioritisation of maintenance and inspection plans for high-risk equipment	• Full risk analysis • Level of acceptability • Reliability levels compared to acceptability thresholds
Decision-making process Comparison of alternatives	• Qualitative hierarchy of actions possible • No optimisation of the costs • Difficult to justify high cost measures	• Optimisation of maintenance and inspection plans based on risk • Cost not included • Definition of the plans possible	• Assessment of cost of life • Optimisation of the maintenance and inspection plans according to the cost

Table 3 – Main concepts for ageing management methodologies

From these above tables, a general frame for the use of methodologies can be shown [IMdR]:

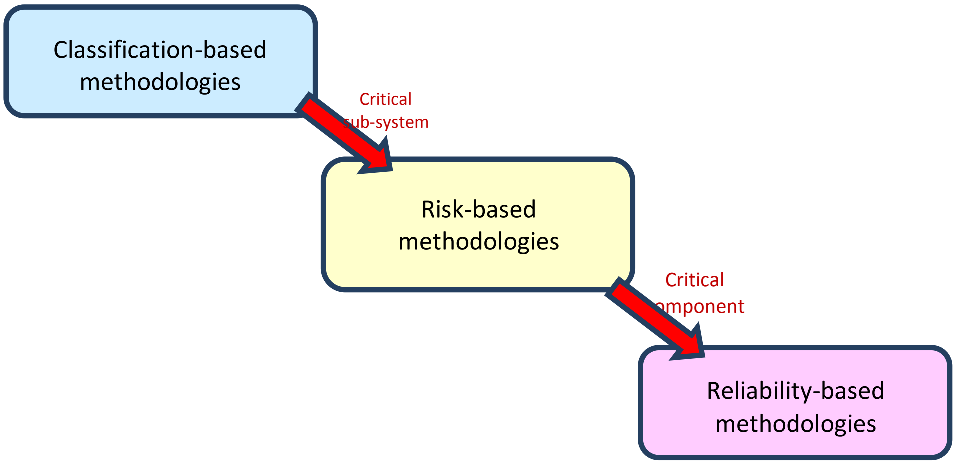


Figure 13: global ageing methodologies framework

The methodology for ageing management is not unique to a defined system. Most of the industry sectors and infrastructure owners use many types of methodologies, depending on the criticality of the component. This criticality can be defined by regulations, risk analysis or cost analysis. There is no specific methodology that integrates all the levels of ageing methodologies. A next step for the project could be to identify possible bridges and interactions between the various methodologies.

5.2 Proceedings of the workshop: possible improvements

A workshop on ageing methodologies was organized in Vienna on 2nd September 2014.

The main objective of the workshop was to identify the following aspects of ageing methodologies:

- Problems with the current practices
- Commonalities and possible improvements

In order to achieve the expected outcomes from the workshop, participants were split into two different groups according to their sector of activity: on the one hand, civil infrastructure and, on the other hand, the industrial/energy sector.

A final discussion led to a conclusion on the commonalities and possible improvements.

The group discussions and analysis of methodologies previously presented led to the identification of the following commonalities and possible interactions:

1. **The applications and developments of methodologies are limited by regulations and non-standardised approaches. One important aspect is that the different regulations do not allow for a common methodology development. The lack of standards has led to multiple "personalised" versions of common methodologies. In order to develop and innovate the methodologies, regulations and standards should be aligned as much as possible all over Europe.**
   Example: Common regulations and standards to classify the condition of an asset or network would lead to more reliability and availability and an optimisation of the lifecycle. The current practice in the different EU countries allows detailed benchmarking to take place. A unique classification system will make it possible to compare and rank the performance of assets and networks. Steps have already been taken in the IRIS project and CEN standardization, but this has still to be moved forward much more. IRIS has developed and standardised the international rating scales in a descriptive manor and has formulated an ageing function. Nevertheless this development covers the small sector of bridges only. The research demand is on widening this concept to other structures, sectors, materials and configurations.

2. **The identification of improvements from one methodology to another is difficult, even if theoretically understood. Some bridges need to be set up to generalise the best approaches**.
   Example: Fragility curves describe the consequence of a hazard (flooding, landslide, earthquake) to an asset of a network (effect of an earthquake on a building, etc.)[Wenzel]. It is a probabilistic approach well developed in European infrastructure and suitable for implementation in industry. While the method is well developed, the application is limited to specific sectors. Research funding is needed to demonstrate the technology in other sectors. The main benefit is better forecasting which leads to better decisions on mitigating measures, thus saving cost. The risk-based methodology from industry could benefit from a simplification of the reliability approach from bridges by use of the fragility curve regarding combined failure modes. Indeed, a fragility curve for ageing could represent the probability of failure for a specific structure, according to time, type of degradation, environment, inspection data, etc. It would be a more extensive model of condition assessment.

3. **For every sector, the benefit of changing/improving methodology is difficult to estimate. A process that could allow this benefit to be evaluated in a long term vision would be very interesting**.

Example: A dedicated COST Action details the benefits of Structural Health Monitoring (SHM[1]) for civil infrastructure owners by the novel utilisation of applied decision analysis on how to assess the value of SHM – even before it is implemented. This improves the decision basis for design, operation and life-cycle integrity management of structures and facilitates more cost-efficient, reliable and safe strategies for maintaining and developing the built environment to the benefit of society. SHM is increasingly applied to collecting information on loads and aggressive environments acting on structures, structural performances, deterioration processes and changes in the use of structures. However, the analysis of SHM data is still an n important challenge. There is an urgent need to establish a better understanding of the value of SHM before its implementation, together with practical- applicable methods and tools for its quantification. This Action thus aims to develop and describe a theoretical framework, together with methods, tools, guidelines, examples and educational activities for the quantification of the value of SHM. The COST Action will be conducted with the support of the Joint Committee on Structural Safety (JCSS). The networks of researchers and industries established during COST Actions TU0601, C26, E55 and E24, the EU FP7 project IRIS, the Marie Curie Network SmartEn and the JCSS will ensure visibility, impact and dissemination. The main advantage is that the method will lead to risk reduction and cost saving. A strong example is given in [Thöns] and [Faber] .

A new COST action will produce clear objectives for a better formulation for the value of monitoring and thus provide a good starting point for future research in this direction. *The method is in development and needs R&D funding after the COST action.*

4. **A global view of risk methodologies to be applied to a structure/equipment/site could be beneficial to help stakeholders to choose or develop their methodologies. The development of dedicated technological platforms could help to achieve this goal.**

   Example: The EQvis monitoring platform is a well-developed risk management tool (TRL 7) that is applied to a number of cases in infrastructure and industry. The platform is GIS-based and will deal with different types of datasets from the asset and performance monitoring. Based on a Consequent Risk management methodology, this open source platform integrates the different tools to estimate damage and consequences of a seismic event. It is a decision tool that could be adapted with tools for ageing damage assessment. Such a platform should be useful to generalise the procedures and methodologies for ageing management and allow a quick analysis of ageing scenario consequences to be carried out. The EQvis open source platform could be used as a starting point to develop such a tool.

5. **Repair methods, change in the operation conditions and their influence on the condition assessment is not always very well integrated in the methodologies. Tool developments could be made to achieve the better integration of modifications in the condition assessment and better monitoring/measurement of the changes.**

   Example: RBI tools for condition assessment are not well adapted to integrating data from inspection, monitoring and maintenance of a structure. Improvements are also needed to measure the changes in environment and tools should be developed to integrate these changes in the condition assessment of the structure.

6. **The methodologies still suffer from a lack of data on degradation/feedback on failure. Most of the methodologies need more statistical data to be more reliable. The process of collecting data and critical failure feedback could be developed and applied to new technologies. Defining the early data collection**

[1] SHM : structural Health monitoring is a tool to translate monitoring data into structural health indicators for permanent damage assessment of a structure.

process when introducing new technologies may help those technologies to demonstrate their ageing characteristics earlier.
Example: the monitoring of new critical equipment could avoid early ageing incidents. As an example, the monitoring of new boilers could have avoided several leaks due to poor welding in the last years.

The proceedings of this workshop are publically available on the project website (www.SafeLife-X.eu-vri.eu).

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