SafeLife-X *Safe Life Extension management of aged infrastructures networks and industrial plants*

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Report on aging concerns

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1 Introduction

The purpose of this task is to identify ageing concerns over several types of civil infrastructures and industrial plants.

Previous WP identified stakeholders' needs and existing standards on the area which will allow this Task to go one step further identifying critical structures and systems concerned by ageing, defining communalities and asset categorization regarding ageing matters.

As a first approach before defining ageing technologies (Task 2.2) and methodologies (Task 2.3), this deliverable is aimed at collecting aged related threats and damage mechanisms. This data will be obtained from: bibliography, partners or Consortium' expertise and from real data obtained from significantaccidents due to ageing. The information will be mainly dedicated to transport infrastructures (road, bridges, tunnels) and energy/industrial plants(wind turbines, hydraulic structures, chemical plants)since they have been identified in WP1 as critical infrastructures that can provoke major disasters.

As a base document for industrial infrastructure ageing concerns, the summary guide "Managing Ageing Plant", written by HSE (2010) which is the national independent watchdog for work-related health, safety and illness of UK, will be used. With respect to civil infrastructures, the results of the Iris European project will be the basis of this report.

2 Objective

This project focuses on critical civil and industrial infrastructures which due to the passage of time or because of over-exploitation are damaged and may not operate in the way for which they were designed or their working capacity and safety may be reduced.

The first step will be the identification of these critical infrastructures, quantifying and locating them around Europe. According to 2008/114CE directive, Critical Infrastructure means an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions. This may include transboundary cross-sector effects resulting from interdependencies between interconnected infrastructures.

A distinction between transport and energy/industrial infrastructures will be undertaken. Afterwards, asset categorization and threats and damage mechanism will be identified so that communalities between civil and industrial infrastructures will be defined.

This information will be complemented with additional data from failure and incidents registered in various databases.

3 Definition of Ageing Concerns

Transport Infrastructures and Industry are vital elements of our economic activities since they provide the bones and the arteries of the creation of added value in the whole value chain. Nevertheless, their ageing is a fact.

Ageing is defined as the evidence or likelihood of significant deterioration and damage taking place since new, or for which there is insufficient information and knowledge available to know the extent to which this possibility exists.

The significance of deterioration and damage relates to the potential effect on the equipment's functionality, availability, reliability and safety. Just because an item of equipment is old does not necessarily mean that it is significantly deteriorating and damaged. All types of equipment can be susceptible to ageing mechanisms.

Ageing is one of many factors that affect performance of infrastructure and industries its robustness against threats posed by common environmental conditions, extreme natural hazards, terrorism, etc.Ageing often acts together with other factors such as design, maintenance, and operation in increasing the vulnerability of infrastructure to these threats (Homeland Security, 2010).

Thisdegradation process implies costs that must face private and public owners. These costs come from various tasks that must be undertaken for determining the origin of the damage and a subsequent intervention on the component. To act before an irreversible harm occurs, which in some cases can become into a catastrophe standardization of ageing, degradation laws and methodologies application have become essential. Standardization particularly helps in a competitive environment like construction to apply innovative technologies. The degradation laws and methodologies, on the other hand, allow determining residual life of existing component and maintenance plans which will give place to a cost optimization.

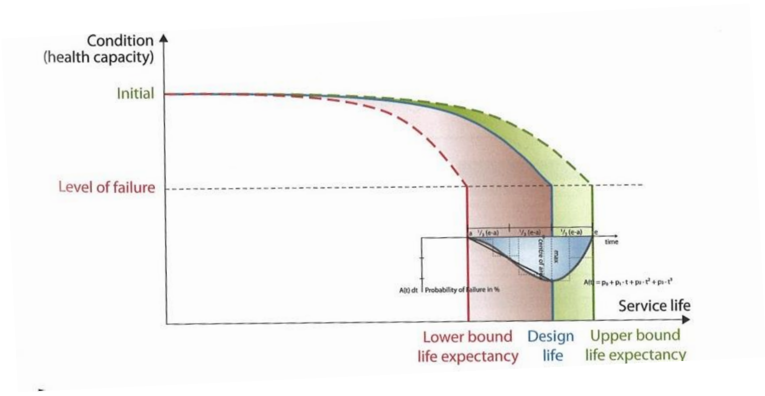

Figure 1: General concept of structural ageing obtained from (Wenzel, 2013).

Nevertheless, damage on transport infrastructure and industry can be significantly reduced if the following aspects are promoted, mainly in the design phase:

- **Resilience:** in engineering, resilience is the capacity for "bouncing back faster after stress, enduring greater stresses, and being disturbed less by a given amount of stress" [Martin-Breen and Anderies, 2001; Longstaff 2005]. This definition is commonly applied to objects. However, most global risks are systemic and a system may show resilience not by returning exactly to its previous state, but instead by finding different ways to carry out essential functions; that is, by adapting [Berkes, 2007]. For a system, an additional definition of resilience is "maintaining system function in the event of disturbance" (see Figure 2).

Figure 2: Resilient systems

A resilient infrastructure is one that has the capability to adapt to changing contexts, withstand sudden shocks and recover to a desired equilibrium (either the previous one or a new one) while preserving the continuity of its operations. The three elements in this definition encompass both recoverability (the capacity for speedy recovery after a crisis) and adaptability (timely adaptation in response to changing environment).

A system is comprised of smaller systems and it is a part of larger systems. The national resilience is composed of five subsystems [World Economic Forum]: economic subsystem, environmental subsystem, governance subsystem, infrastructure subsystem and social subsystem. Infrastructure subsystem includes aspects such as critical infrastructure (namely communications, energy, transport, water and health).

The resilience is composed of *resilience characteristics* and *resilience performance*. The former components are robustness, redundancy and resourcefulness; the later components are response and recovery.

- **Robustness** incorporates the concept of reliability and refers to the ability to absorb and withstand disturbances and crises. Robust systems are inherently more resilient. Example of attributes:
  - Monitoring system health: regularly monitoring and assessing the quality of the subsystem ensures its reliability.
  - Modularity: mechanisms designed to prevent unexpected shocks in one part of a system from spreading to other parts of a system can localize their impact.
  - Adaptive decision-making models: networked managerial structures can allow an organization to become more or less centralized depending on circumstances.

- **Redundancy:** it involves having excess capacity and back-up systems, which enable the maintenance of core functionality in the event of disturbances (Berkes, 2007).
  - Redundancy of critical infrastructure: designing replication of modules which are not strictly necessary to maintaining core function day to day, but are necessary to maintaining core function in the event of crises.
  - Diversity of solutions and strategy: promoting diversity of mechanisms for a given function. Balancing diversity with efficiency and redundancy will enable communities and countries to cope and adapt better than those that have none.

- **Resourcefulness:** it means the ability to adapt to crises, respond flexibly and – when possible – transform a negative impact into a positive. Example of attributes:
  - Capacity for self-organization(Berkes, 2007): This includes factors such as the extent of social and human capital, the relationship between social networks and state, and the existence of institutions that enable face-to-face networking. These factors are critical in circumstances such as failures of government institutions when communities need to self-organize and continue to deliver essential public services.

  - Creativity and innovation: In countries and industries, the ability to innovate is linked to the availability of spare resources and the rigidity of boundaries between disciplines, organizations and social groups (Swanson et al., 2009).

- **Response.** It means the ability to mobilize quickly in the face of crises (Bruneau et al, 2003). This component of resilience assesses whether a nation has good methods for gathering relevant information from all parts of society and communicating the relevant data and information to others, as well as the ability for decision-makers to recognize emerging issues quickly. Example of attributes:
  - Communication: Effective communication and trust in the information conveyed increase the likelihood that, in the event of a crisis, stakeholders are able to disseminate and share information quickly, and to ensure cooperation and quick response from the audience.
  - Inclusive participation: Inclusive participation among public sector, private sector and civil society stakeholders can build a shared understanding of the issues underpinning global risks in local contexts, reduce the possibility of important interdependencies being overlooked (Ozdemir et al, in press) and strengthen trust among participants (Swanson et al, 2009).

- **Recovery.** It means the ability to regain a degree of normality after a crisis or event, including the ability of a system to be flexible and adaptable and to evolve to deal with the new or changed circumstances after the manifestation of a risk (Bruneau, 2003).Example of Attributes:
  - Active "horizon scanning": Critical to this attribute are multi-stakeholder processes tasked with uncovering gaps in existing knowledge and commissioning research to fill those gaps (Amanatidou et al., 2012).
  - Responsive regulatory feedback mechanisms: Systems to translate new information from horizon-scanning activities into action – for example, defining "automatic policy adjustments triggers" – can clarify circumstances in which policies must be reassessed (Swanson, 2009).

It is important to also consider the cultural and historical significance of aging infrastructure as it relates to security. There are many bridges, monuments, and buildings across the nation that could be classified as historically significant. This classification increases the vulnerability of a structure without any other factors being considered due to the potentially negative effect on morale as a result of its loss. In terms of attractiveness, terrorists seek out targets that will disrupt the public's perception of safety and security, produce a large number of casualties, and a high amount of collateral damage. Providing safety and security countermeasures for these types of structures is especially challenging, as it needs to be subtle, economical, and effective [Homeland].

4 Factors Potentially Reinforcing Infrastructure Age Problems

Transport and Industry infrastructures age problems may be caused by several threats and hazards specified below:

Figure 3: Threats and hazards for infrastructures

5 Which Is Impacted By Ageing?

This section identifies which critical elements are impacted by ageing.In fact, the passage of time, through environmental exposure and industrial processes, affects any element. Depending on the "aggressiveness" of the process and/or the work environment, the impact will be more or less obvious and more or less important.

According to Oxford Dictionary, Infrastructure is basic physical and organizational structures needed for the operation of a society or enterprise, or the services and facilities necessary for an economy to function(Sullivan et al, 2003). It can be generally defined as the set of interconnected structural elements that provide framework supporting an entire structure of development. It is an important term for judging a country or region's development.

The term typically refers to the technical structures that support a society, such as roads, bridges, water supply, sewers, electrical grids, telecommunications, and so forth, and can be defined as "the physical components of interrelated systems providing commodities and services essential to enable, sustain, or enhance societal living conditions." (Fulmer, 2009)

Critical infrastructures could be classified as follows:

Production

- Industrial plants (chemical plants, asset manufacturing).
- Power plants (nuclear, hydraulic, renewable, etc.)
- Extraction and treatments stations of gas/petroleum/raw materials.

Distribution

- Electric energy distribution network.
- Water distribution network.
- Gas/petroleum distribution network.

Transport

- Ground transportation: roads, train/metro railways.
- Air transport: airports.
- Marine transport: harbours.

Storage area

- Gas/petroleoum/raw material warehouse/tanks.
- First necessity consumer goods warehouse, eg, food.
- Reservoir.

Public health

- Sanitary network (hazardous waste management, waste water, garbage, etc.).
- Hospitals.
- Emergency services.

This project will focus on the following critical infrastructures which will be divided into twomain groups: transport infrastructures and energy/industrial plants.

Transport infrastructures:

- Bridges
- Tunnels
- Roads
- Railways

Energy/Industrial plants

- Chemical plants
- Energy plants
- Wind turbines
- Hydraulic structure
- Networks: hazardous liquid distribution pipelines network, gas & electricity grid

5.1 Transport infrastructures

Frameworks cannot be shared by different types of infrastructures, which can be distinguished as:

Asset	Elements
Bridges	Substructure: Footing/foundation, abutments and piles/column/pier. Superstructure: Beams, deck, towers, ties/cables. Bearings. Joints.
Tunnels	Crown, invert, walls/faces and floor. Shield and lining. Dowels and bolts. Portals.
Roads	Pavement, drains and culverts, kerbs and footpaths, railings and guardrails, horizontal and vertical signs.
Railways	Formation, ballast, sleepers/ties, rails, fastenings, fittings (switches and crossings), catenary.

Technological challenges

Focusing on transport infrastructures, and in order to identify technological challenges, firstly current situation should be evaluated by means of looking into the following aspects:

- Damage assessment methods and existing metrics for aging.
- Mitigation practices.
- Common intersecting issues among infrastructures to be utilized for better efficiency in improving safety and reducing costs.
- Decisionmaking procedures in managing retrofitting and prioritizing infrastructure (on different levels). Limitations and advantages.
- Specific hazards that afflict aging infrastructure (deterioration, sustainability, energy, obsolescence, wear and tear, etc.) and manmade hazards.
- Role of:
    - emerging engineering paradigms (performance-based considerations, resiliency, multihazards, etc.)
    - advanced technologies (superior materials, advanced systems, increased redundancies, etc.).
    - Information Technologies such as monitoring.

The challenges should be aimed at enabling an extension of the useful life-time of aged infrastructures:

- favoring component rather than full systems replacement and
- introducing sophisticated cost, risk, performance and resource analysis through the new Strategic Assets Lifecycle Value Optimization

- Better align infrastructure investments with economic development goals

BRIDGES

- Maintenance and repair management. Advanced decision making techniques, including methods to prioritise investment.
- Advanced materials
- Apply collected data to decisionmaking process
- Funding for bridge inspections must increase. Better training and advanced technologies for bridge inspectors
- How to apply collected data from inspection and monitoring to decision making processes
- Causes of failure or deterioration
- Incorporate aging in the national bridge databases
- Standardised methods to prioritise investment

TUNNELS

- Better design, components and installation to avoid electrical and wiring system degradation
- Controlling water leaks and other drainage issues
- Ceiling slab concrete and support deterioration
- Low cost repair of tile delamination
- Easy wall cleaning strategies for actual washing equipment, considering wall surface obstructions.
- Easy replacement of difficult light fixture cleaning with modern fixtures
- Improve maintenance techniques for ventilation fan motor drive equipment and plenum dampers
- Reduce the maintenance needs of sensors for CO_2 and for environmental air quality
- Keeping the air ducts free of dust accumulation
- Avoiding obsolescence of electronic components

ROADS

- Surface repair methods
- Strengthening for increased bearing capacity
- Extending the capacity by geometric modification
- Novel materials for increased durability and lifespan of new road infrastructures
- Rapid, non-intrusive construction and maintenance systems and techniques

RAILWAYS

- Rail Maintenance efficiency through new solutions for Rail Asset Registers.
- Measuring and monitoring tools, maintenance engineering
- Rapid, non-intrusive construction and maintenance systems and techniques

5.2 Energy/Industrial plants

According to HSE, the following industrial sub-components can be distinguished:

- Primary Containment Systems (Process and Utilities)
- Control & Mitigation Measures
- EC&I Systems
- Structures

Asset Type	Examples
Primary Containment Systems (Process and Utilities)	Static Elements – vessels, pipework and fittings, whether at significant pressure or not, etc
	Rotating / Motive Elements
Control & Mitigation Measures	Process Safeguard Systems
	Secondary or Tertiary Containment Systems.
	Control and Mitigation Systems.
	External Hazard/Environmental Safeguards.
EC&I Systems	EC&I -safety critical process safeguarding systems (trips, alarms, process ESD, etc).
	EC&I -safety critical leak detection and response systems (fire and gas leak / area detection, emergency shutdown systems).
	Integrity and availability of key services such as power supply, UPS, emergency backup generators, battery units, etc.
	CCTV Monitoring of plant areas and escape routes, etc.
Structures	Supporting structures, civil features and foundations for: • Primary containment • Secondary and tertiary containment • Providing impact protection • Safe places of work • Access and escape routes • Safety critical services and utilities
	Safety critical EC&I equipment, weatherproofing, ingress protection, etc. Structures and civils features that could impact major hazard plant, pipelines or equipment (including EC&I and safeguarding equipment, cabling, etc) were they to collapse / fail or which could disperse spilt material if they were to leak/ fail.

<u>Technological challenges</u>

The main challenge addressing safety issue in industrial facilities and power plants is to develop methods to maintain safety of aged and repaired structures. To do so, and from a technological perspective, several goals must be achieved, which are the following:

- Record and study the structures responses to daily, environmental or test loads
- Assess the theoretical structure design in front of the real implementations
- Assess the performance of the use of new material in structures
- Follow the structures performance along its useful life in order to make easy their preservation
- Damage localization to make early repairs
- Damage identification before structure collapses

The accomplishment of objectives showed above allows life extension of involved equipment and infrastructures. The provision of Structural Health Monitoring (SHM), reliability based design and risk based inspection strategies highly support this issue.

Additionally, and in order to minimise the ageing impact, industrial systems must be adaptable to changing requirements. According to The European Technology Platform on Industrial Safety, the industrial sector should focus on adopting reliable wireless technologies, data collection and analytics methods, inspection planning, scheduling approaches and lifetime assessment from specific failure modes, considering safety criteria and security factor.

According to Nitoi and Rodionov (2010), for short and medium lived, active components (relays, controllers, valves, pumps,) ageing information can be obtained from operating experience, including both failure and maintenance information. For long lived, structural parts and passive components (pipes, cables, structures), there is no planned preventive or corrective maintenance, and ageing information is typically in the form of degradation data from condition monitoring, surveillance and inspection programs.

The participation of plant personnel in qualitative analyses represents an important aspect of the analysis, because it can reveal many issues, as failures that are not caused by ageing.

Difficulties:

- the completeness of stressors list and potential ageing mechanism,
- large amount of information that should be consulted

The major problem of qualitative assessment is that is very time-consuming and resource-intensive.

6 Key Ageing Mechanisms

Some of the most common degradation mechanisms are briefly described within this section. Each specific mechanism can be dependant of the process nature, dependant of their causes or a combination of several of them.

Considering the nature of the degradation process (see Figure 4), ageing mechanisms could be classified into:

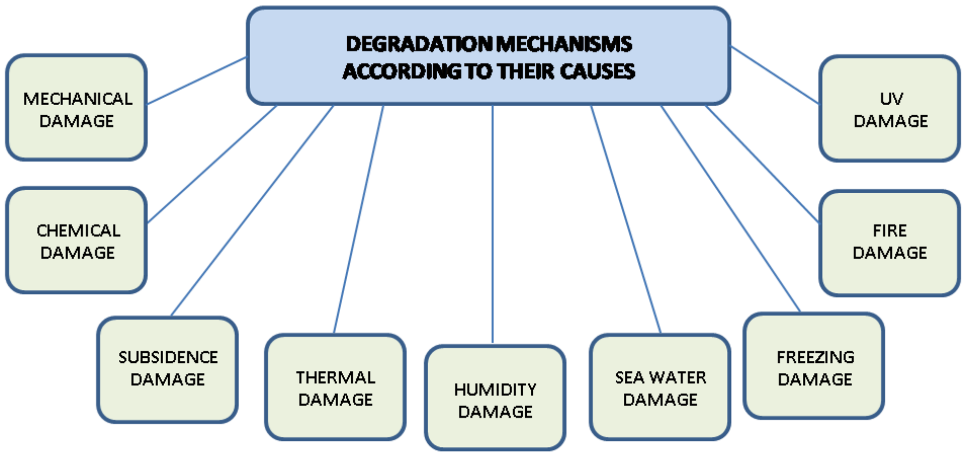

Figure 4: Degradation mechanism according to the process causes

MECHANICAL DAMAGE

Mechanical damage in static, dynamic and rotatory elements is one of the most typical causes of degradation. For dynamic and rotatory elements, a severe vibration processmay lead to cracks and looseness in the crotch area of the materials. The effects of this kind of damage in infrastructure materials are: changes in shape, changes in axial alignment, in material properties, in local distributinos of stress and strain, and/or local loading and the introduction of other anomalies or defects. For static elements, repeated loads may lead to fatigue cracks with similar consequences.

CHEMICAL DAMAGE

As mentioned above in the case of the nature of the degradation process, chemical damage involves the direct effect of atmospheric or biologically produced chemicals in the breakdown, and it changes the composition of the materials into a solution that has different chemical or mechanical properties than the original substance.

SUBSIDENCE DAMAGE

The motion of a surface, usually origined by mining processes and natural earthquakes, may cause important wreak havoc in structures and buildings. Fixed parts are more vulnerables to subsidence, since they are more likely to suffer from cracking in those situations. Soft malleable and flexible materials are used to prevent from cracking or crazing caused by subsidence damage.

THERMAL DAMAGE

There exists a thermal damage caused by cold temperatures and a thermal damage caused by hot temperatures. Thermal capability of infrastructures varies a lot depending on the materials they are made of, its location and its specific role. In all cases, and as a preventive measure, thermal exposure time must be minimized to avoid a degradation effect.

HUMIDITY DAMAGE

Damages caused by water exposure are very typical in external infrastructures and equipment, such as bridges, roads or telecommunications networks. Adequate materials and system protection are required in order to mitigate the effect of humidity, keeping the structure dry and clean. Water presence may cuase wet corrosion, an electrochemical mechanism that takes place if water is present in the environment (also water present as vapour in the atmosphere).

SEA WATER DAMAGE

This is a special case of humidity damage, since sea water include abrasive material (mainly salt particles) able to have a heavy corrosive effect over strcutures. As a consequence of abrasion caused by hard particles impacting the surface of the infrastructure, there is a surface wear that results in loss of material (commonly identified as an erosion effect). The problem is critical regarding marine equipment and infrastructures that are close to the sea. In these cases spcial materials, more resistant to abrasion, are employed (i.e.: fibreglass or carbon).

FREEZING DAMAGE

Freezing damage is caused when temperatures are low enough to produce a negative impact in the materials that are part of the structure. Frozen parts can provoke a bursting effect caused by the added pressure when water expands, cracking or seriously damaging the structure. Frost-thaw cycles accelerate materials damage provoking early ageing of structures. Water pipes, for instance, are usually exposed to this kind of degradation mechanism.

UV DAMAGE

Many materials are attacked by ultra-violet radiation (especially polymers) and may crack or disintegrate, if they're not UV-stable. The UV degradation is a common problem in products exposed to sunlight. Continuous exposure is a more serious problem than intermittent exposure, since attack is dependent on the extent and degree of exposure.

7 Data From Failure And Incident

7.1 Transport Infrastructures

According to the US Department of Homeland Security, engineering structures must succeed in three domains: the theoretical, the physical, and the social. The operating tools of these domains are abstract analysis, empirical application, and economics. Whether successful or not, the required synthesis is particularly spectacular in long-span bridges, among which the suspension ones are the undisputed champions.

With regard to bridges, for instance, despite the advances in abstract analysis and controlled testing, failures have the most conspicuous influence on bridge design, construction, and management.

Suspension bridges represent a small portion of the total bridge population; however, they are essential to transportation, and at the forefront of engineering innovation. Consequently their failures are critically important not only quantitatively but also qualitatively.

Citing earlier work by Sibly and Walker in England, he argues that each innovative bridge form is developed by trial and error until its limits are surpassed and spectacular failure occurs. Only then does theory catch up with the practice and fully explains the structural behavior. By this estimate, the still evolving cable-stayed bridges should be viewed with particular concern.

Two popular examples may be Tacoma Bridge (1940) and Silver Bridge (1967). The more complex dynamic behavior of these structures resulted in greater lapses in the designer’s knowledge, and hence, the many failures under wind loads, as well as those caused by rushing crowds.

Nevertheless, numerous failures occured in different type of bridges can be listed along the History.

Table 1: List of bridge failures.

Bridge	Location	Date	Construction type	Reason
Stirling Bridge	Stirling, Scotland	1297	Beam and trestle over the River Forth	Overload
Rialto Bridge	Venice, Italy	1444	Wooden structure with central drawbridge.	Overload.
Saalebrücke bei Mönchen-Nienburg	Nienburg, Saxony-Anhalt, Germany	1825	Chain-stayed bridge with small bascule section	Bad material, unbalanced load and vibrations
Broughton Suspension Bridge	Broughton, Manchester England	1831	Suspension bridge over River Irwell	Resonance
Yarmouth Bridge	Great Yarmouth England	1845	Suspension bridge	Overload

Dee Bridge	Chester England	1847	Cast iron beam bridge over the River Dee	Overload
Angers Bridge	Angers France	1850	Suspension bridge over Maine River	Wind and resonance
Gasconade Bridge	Gasconade, Missouri USA	1855	Wooden rail bridge	Inauguration before bridge's temporary trestle work was replaced with permanent structure
Desjardins Canal Bridge	Desjardins Canal, Ontario Canada	1857	Rail bridge	Mechanical force due to broken locomotive front axle
Sauquoit Creek Bridge	3 miles (4.8 km) from Utica, New York USA	1858	Railroad trestle	Overload
Springbrook Bridge	Between Mishawaka and South Bend, Indiana USA	1859	Railroad embankment bridge	Natural hazard (washout)
Wootton Bridge	Wootton England	1860	Cast iron rail bridge	Fatigue failure
Bull Bridge	Ambergate England	1860	Cast iron rail bridge	Fatigue failure
Platte Bridge	St. Joseph, Missouri USA	1861		Sabotage
Chunky Creek Bridge	near Hickory, Mississippi USA	1863		Natural hazard (washout).
Train bridge	Wood River Junction USA	1873		Natural hazard (washout)
Portage Bridge	Portageville, New York USA	1875	Wooden beam bridge over the Genesee River	Fire
bridge	between Valparaiso and Santiago Chile	1875		Collapsed beneath the overnight train
Ashtabula River	Ashtabula, Ohio	1876	Wrought iron truss bridge	Fatigue failure

Railroad Bridge	USA			
Tay Rail Bridge	Dundee Scotland	1879	Continuous girder bridge, wrought iron framework on cast iron columns, railway bridge	Faulty design, construction and maintenance, collapsed because of structural deterioration and wind load exceeding estimate
Inverythan Rail Bridge	Aberdeenshire Scotland	1882	Cast iron girder rail bridge	Bad material (hidden defects in cast iron)
	Little Silver, New Jersey USA	1882	Trestle railway bridge	Insecure railroad
Camberwell Bridge	London England	1884	Cast iron trough girder bridge over railway	Bad material (hidden defects in cast iron)
Bussey Bridge	Boston USA	1887	Iron railroad bridge collapses under train	poor construction
Big Four Bridge	Louisville, Kentucky USA	1888	caisson and truss	During construction
Norwood Junction Rail Bridge	London England	1891	Cast iron girder fails under passing train	Bad material (hidden defects in cast iron)
Munchenstein Rail Bridge	Munchenstein Switzerlaand	1891	wrought iron truss	Impact
Point Ellice Bridge	Victoria, British Columbia Canada	1896		Overloaded
Dry Creek Bridge	Eden, Colorado USA	1904	Wooden railway bridge	Natural hazard (washout)
Egyptian Bridge	Saint Petersburg, Russia	1905	Stone suspension bridge	Overload
Portage Canal Swing Bridge	Houghton, Michigan USA	1905	Steel swing bridge	Impact.
Cimarron River Rail Crossing	Dover, Oklahoma Territory USA	1906	Wooden railroad trestle	Natural hazard (washout)

Quebec Bridge	Quebec City Canada	1907	Cantilever bridge, steel framework, railway bridge	Collapsed during construction: design error.
Romanov Bridge	Zelenodolsk Russia	1911	Railway bridge	Collapsed during construction: ice slip undermined scaffolding
Division Street Bridge	Spokane, Washington USA	1915	Steel framework, trolley car bridge	Bad material, fatigue.
Quebec Bridge	Quebec City Canada	1916	Cantilever bridge, steel framework, railway bridge	During construction due to contractor error
	Otsu Japan	1934		Natural Hazard (Typhoon)
Swan River Railroad Bridge	Fremantle Australia	1926		Natural Hazard (Flood)
Falling Creek Bridge	Chesterfield County, Virginia USA	1936	Wood and steel.	Impact
Kasai River Bridge	Kasai Belgian Congo	1937	Railway bridge	While under construction.
Upper Steel Arch Bridge	Niagara Falls, NY Canada	1938	Steel arch road bridge	Natural hazards (ice)
Sandö Bridge	Kramfors, Ångermanland Sweden	1939	Concrete arch bridge	Collapsed during construction
Tacoma Narrows Bridge	Tacoma, Washington USA	1940	Road bridge, cable suspension with plate girder deck	Poor design
Theodor Heuss Bridge	Ludwigshafen Germany	1940	Bridge of concrete, Motorway bridge	Collapsed during construction
Chesapeake City Bridge	Chesapeake City, MD USA	1942	Road bridge, vertical lift drawbridge	Impact
Ludendorff Bridge	Remagen Germany	1945	Truss railroad and pedestrian bridge	Impact
John P. Grace Memorial	Charleston, South Carolina	1946	Steel cantilever truss automobile bridge	Impact

Bridge	USA			
Inotani Wire Bridge	Toyama Japan	1949		
Duplessis Bridge	Quebec Canada	1951	Steel bridge	Natural hazard (adverse temperature)
Harrow & Wealdstone Station Footbridge	Wealdstone England	1952	Pedestrian footbridge	Impact
Whangaehu River Rail Bridge	Tangiwai New Zeland	1953	Railway bridge	
St. Johns Station Rail Bridge	Lewisham, South London England	1957	Railway bridge	Impact
Temporary footbridge	Havana Cuba	1958	Temporary footbridge	Impact
Second Narrows Bridge	Vancouver, British Columbia Canada	1958	Steel truss cantilever	Collapsed during construction due to bad design
Severn Railway Bridge	Gloucestershire England	1960	Cast iron	Impact
King Street Bridge	Melbourne Australia	1962		Natural hazard (high load added to a very cold winter day)
General Rafael Urdaneta Bridge	Maracaibo Venezuela	1964	Road bridge	Impact
Kansas Avenue Bridge	Topeka, Kansas USA	1965	Kansas Avenue Melan Bridge for traffic between downtown and North Topeka	Structural deterioration
Heron Road Bridge	Ottawa Canada	1966	Concrete road bridge	Bad design
Boudewijnsnelweg Bridge	Viersel Belgium	1966	Concrete road bridge over Nete Canal (Netekanaal)	Bad design
Heiligenstedten Bascule Bridge	Heiligenstedten Germany	1966	Road bridge	Impact

Silver Bridge	Point Pleasant, West Virginia and Gallipolis, Ohio USA	1967	Road bridge, chain link suspension	Bad material
Queen Juliana Bridge	Willemstad, Curaçao Netherlands	1967	Portal bridge	During construction
Countess Weir Bridge	Exeter, Devon England	1968	Brick Arch bridge	During construction
Britannia Bridge	Menai Strait Wales	1970	Railway tubular bridge	Accidental failure
West Gate Bridge	Melbourne Australia	1970	Road Bridge	Bad design
Cleddau Bridge	Pembroke Dock and Neyland Wales	1970	Box girder road bridge	Bad design
South Bridge, Koblenz	Koblenz Germany	10 November 1971	Road bridge	
Sidney Lanier Bridge	Brunswick, Georgia USA	1972	Vertical Lift Bridge over the South Brunswick River	Impact
Welland Canal Bridge No. 12	Port Robinson, Ontario Canada	1974	Vertical lift bridge over the Welland Canal	Impact
Makahali River bridge	Baitadi Nepal	November 1974		
Tasman Bridge	Hobart Australia	5 January 1975	Bridge of concrete, Motorway bridge	Impact
Reichsbrücke	Vienna Austria	1 August 1976	Road bridge with tram	Bad design
Granville Railway Bridge	Sydney Australia	1977	Vehicle overpass	Impact.
Benjamin Harrison Memorial Bridge	Hopewell, Virginia USA	1977	Lift bridge	Impact
Green	Troy, New York	1977	Lift bridge	Natural hazard

Island Bridge	USA			(flooding)
Hood Canal Floating Bridge (William A. Bugge Bridge)	Olympic, Washington USA	1979	Floating bridge	Overload
Almöbron (Tjörnbron)	Stenungsund Sweden	1980	Steel arch bridge	Impact
Sunshine Skyway Bridge	near St. Petersburg, FL USA	1980	Steel cantilever bridge	Impact
Hayakawa wire bridge	Saito, Kyūshū Japan	1980	Wire bridge (?)	Lack of inspection and maintenance
Hyatt Regency walkway collapse	Kansas City, Missouri USA	1981	Double-deck suspended footbridge in hotel interior	Bad design and Overload
Cline Avenue over the Indiana Harbor and Ship Canal	East Chicago, Indiana USA	1982	Indiana State Route 912	During construction
Ulyanovsk railway bridge	Ulyanovsk USSR	1983	Railway bridge	Impact
Mianus River Bridge	Greenwich, Connecticut USA	1983	Interstate 95 (Connecticut Turnpike) over the Mianus River	Metal corrosion and fatigue/Deferred maintenance
Amarube railroad bridge	Kasumi, Hyōgo Japan	1986		Natural hazard (Strong wind)
Schoharie Creek Bridge collapse Thruway Bridge	Fort Hunter, New York USA	1987	I-90 New York Thruway over the Schoharie Creek	Bad desing
Schoharie Creek's Mill Point Bridge	Wellsville, Amsterdam, NY USA	1987	State highway	Natural Hazard (Flooding)
Glanrhyd Bridge	Carmarthen Wales	1987	River Tywi	Natural Hazard (washout)
Aschaffenburg Main	Aschaffenburg	1988	Bridge of Motorway 3 over	Bad design

River Freeway Bridge	Germany		River Main	
Sultan Abdul Halim ferry terminal bridge	Butterworth, Penang Malaysia	1988		
Tennessee Hatchie River Bridge	Between Covington, Tennessee and Henning, Tennessee USA	1989	Northbound lanes of U.S. 51 over the Hatchie River	Natural hazard (Shifting river channel)
Injaka Bridge Collapse	Bushbuckridge, Mpumalanga South Africa	1989	300m 7-span continuous pre-stressed concrete road bridge over the Ngwaritsane River under construction.	Bad design
Cypress Street Viaduct	Oakland, California USA	1989	I-880 (Nimitz Freeway)	Natural Hazard (earthquake)
San Francisco – Oakland Bay Bridge	connects San Francisco and Oakland, California USA	1989	I-80	Natural Hazard (earthquake)
Swinging Bridge	Heber Springs, Arkansas USA	1989	Pedestrian suspension bridge over the Little Red River	Resonance
Lacey V. Murrow Memorial Bridge	Connects Seattle and Bellevue, Washington USA	1990	I-90	Natural Hazard (flooding)
Astram Line steel bridge	Hiroshima Japan	1991	Metro railway	During construction.
Claiborne Avenue Bridge	9th Ward, New Orleans, Louisiana USA	1993	Bridge connecting the "upper" and "lower" 9th Wards	Impact
Kapellbrücke (Chapel Bridge)	Lucerne Switzerland	1993	The oldest wooden bridge in Europe, and one of Switzerland's main tourist attractions.	Fire
CSXT Big Bayou Canot rail	near Mobile, Alabama USA	1993	Railroad bridge span crossing Big Bayou Canot of Mobile River	Impact

bridge				
Temporary bridge	Hopkinton, New Hampshire USA	1993	Single-lane temporary bridge in construction zone	Collapsed while being dismantled
Seongsu Bridge	Seoul South Korea	1994	Cantilever Bridge crossing Han River	structural failure-Bad welding
I-5 Bridge Disaster	Coalinga, California USA	1995	Concrete truss bridge Arroyo Pasajero	Structural failure—support piers collapsed
Walnut Street Bridge	Harrisburg, Pennsylvania USA	1996	Truss bridge	Natural hazard (flooding)
Koror-Babeldaob Bridge	Koror and Babeldaob Palau	1996		Collapse following strengthening work
Baikong Railway bridge	Ruyuan, Guangdong China	1996		During construction
Maccabiah bridge collapse	Tel Aviv Israel	1997	Athletes pedestrian Bridge	Poor design and construction
Eschede train disaster	Eschede Germany	1998	Road bridge	Impact
Hoan Bridge	Milwaukee, Wisconsin USA	2000	Concrete and steel bridge	Natural hazard (cold weather)
Hintze Ribeiro disaster	Portugal	2001	Masonry and steel bridge built in 1887	Accidental
Asagiri footbridge	Akashi, Hyōgo Japan	2001		Impact
Queen Isabella Causeway	Texas USA	2001	Concrete bridge for vehicle traffic over Laguna Madre	Impact
Kadalundi River rail bridge	Kadalundi India	2001	140-year old rail bridge collapsed	
I-40 bridge disaster	Webbers Falls, Oklahoma USA	2002	Concrete bridge for vehicle traffic over Arkansas River	Impact
Rafiganj rail bridge	Rafiganj India	2002		Terrorists sabotaged

Interstate 95 Howard Avenue Overpass	Bridgeport, Connecticut USA	2004	Girder and Floorbeam	Impact
C-470 overpass over I-70	Golden, Colorado USA	2004		Bad design
Kinzua Bridge	Kinzua Bridge State Park, Pennsylvania USA	2003	Historic steel rail viaduct	Natural Hazard (tornado)
Sgt. Aubrey Cosens VC Memorial Bridge,	Latchford, Ontario, Canada	2003		Natural hazard (cold) + load
Loncomilla Bridge	San Javier Chile	2004	Concrete bridge for vehicle traffic over Maule River	Bad design
Mungo Bridge[16]	Cameroon	2004	Steel girder for road traffic	
Igor I. Sikorsky Memorial Bridge replacement project	Connecticut USA	2004		During demolition
Big Nickel Road Bridge	Sudbury, Ontario Canada	2004		
Veligonda Railway Bridge	India	2005	Railway bridge	Natural hazard (flooding)
Almuñécar motorway bridge	Almuñécar, Granada Spain	2005	Motorway bridge	during construction,
, Viaduct #1	Tacagua Venezuela	2006	Highway viaduct over a gorge	Natural hazard (Landslides)
E45 Bridge	Nørresundby Denmark	2006	Road bridge	Collapsed during reconstruction
Highway 19 overpass at Laval (De la Concorde Overpass collapse)	Laval, Quebec Canada	2006	Highway overpass	Bad design and bad material
Yekaterinburg bridge	Yekaterinburg	2006		Collapse during construction

collapse	Russia			
Nimule	Nimule Kenya/Sudan	2006		Impact
Pedestrian bridge	Bhagalpur India	2006		During dismantling
Railway bridge	Eziama Nigeria	December 2006		Unknown
Run Pathani Bridge Collapse	Karachi, Pakistan	2006		
Gosford Culvert washaway	Australia	2007		
Highway 325 Bridge over the Xijiang River	Foshan, Guangdong China	2007	Motorway bridge	Impact
Minneapolis I-35W bridge over the Mississippi River	Minneapolis, Minnesota China	2007	arch/truss bridge	Bad design
Tuo River bridge	Fenghuang, Hunan China	2007	unknown	Bad material and bad construction
Harp Road bridge[24]	Oakville, Washington USA	2007	Main thoroughfare into Oakville over Garrard Creek, Grays Harbor County	Overload
MacArthur Maze	Oakland, California USA	2007		Impact
Shershah Bridge - Section of the Northern Bypass, Karachi	Karachi Pakistan	2007	Overpass bridge	Investigation underway
Can Tho Bridge	Cần Thơ Vietnat	2007		Investigation underway
	South eastern Guinea	2007		Overload

Chhinchu suspension bridge	Nepalgunj, Birendranagar Nepal	2007		Overloaded
	South Korea	2007		during construction
Jiujiang Bridge	Foshan, Guangdong province China	2007		Impact
Water bridge	Taiyuan, Shanxi province China	2007		Overloading
Flyover bridge	Punjagutta, Hyderabad, Andhra Pradesh India	2007		During construction
Jintang Bridge	Ningbo, Zhejiang province China	2008		Impact
Road bridge	Studénka Czech Republic	2008		Impact
The Cedar Rapids and Iowa City Railway (CRANDIC) bridge	Cedar Rapids, Iowa USA	2008	Railroad bridge	Natural hazards (flooding)
Somerton Bridge	Somerton, NSW Australia	2008	Timber road bridge	Natural hazards (flooding)
Devonshire Street pedestrian bridge	Maitland NSW Australia	2009	Footbridge	Overloading
Bridge on SS9 over River Po	Piacenza Italy	2009	Road bridge	Natural hazards (flooding)
9 Mile Road Bridge at I-75	Hazel Park, Michigan USA	2009	Road Bridge	Impact
Malahide Viaduct	Broadmeadow, Dublin Ireland	2009	Railway bridge	

San Francisco – Oakland Bay Bridge	San Francisco - Oakland, California USA	2009	I-80	Bad design of repairs.
Tarcoles Bridge	Orotina Costa Rica	2009	Suspension bridge	Overloading
Railway Bridge RDG1 48	Feltham England	2009	Brick arch railway bridge built 1848	Undermined by scour from river
Northside Bridge, Workington. Navvies Footbridge, Workington. Camerton Footbridge, Camerton. Memorial Gardens footbridge, Cockermouth. Low Lorton Bridge, Little Braithwaite Bridge.	Cumbria England	2009	Traditional sandstone bridges.	Natural hazard (rainfall)
Kota Chambal Bridge	Kota, Rajasthan India	2009		
Myllysilta	Turku Finland	2010		Structural failures
Gungahlin Drive Extension bridge	Canberra Australia	2010	Concrete road bridge	Under investigation
Overbridge over Chengdu-Kunming Freeway	Zigong China	2011		Impact
No. 3 Qiantang River Bridge over Qiantang River	Hangzhou, Zhejiang province China	2011		Overloading
Gongguan Bridge	Wuyishan, Fujian province China	2011		Overloading

Baihe Bridge in Huairou district	Beijing China	2011		Overloading
Kutai Kartanegara Bridge	Tenggarong, East Kalimantan Indonesia	2011	Suspension bridge	During repairs. (Under investigation)
Eggner Ferry Bridge over the Tennessee River	Between Trigg County, Kentucky and Marshall County, Kentucky USA	2012	Truss Bridge	Impact
Yangmingtan Bridge over the Songhua River	Harbin China	2012	Suspension Bridge	Overloading
Bridge under construction in Lade	Trondheim Norway	2013		During construction
I-5 Skagit River Bridge collapse	Mount Vernon, Washington USA	2013	Polygonal Warren through truss Bridge	Overloading
Scott City roadway bridge collapse	Scott City, Missouri USA	2013	Concrete road bridge	Impact
Wanup train bridge	Sudbury, Ontario Canada	2013	Steel bridge	Impact
CPR Bonnybrook Bridge	Calgary, Alberta Canada	27 June 2013	Steel railroad bridge	Natural hazard (flooding)

As it can be observed from previous table, main failures occured in bridges, which could be avoided, are caused by inappropriate design and poor maintenance (corrosion, scour, etc.). On the contrary, there are other causes that are more difficult to avoid, such as natural hazards, accidental impacts and overloads.

With regard to tunnels, the Govermment of the Hong Kong Special Administrative Region has listed the failures up to 2012.

Table 2: List of tunnels failures up to 2012.

Tunnels	Location	Date	Reason
Green Park	London	1964	The crown of the shield

Tunnels	Location	Date	Reason
			penetrated through the Clay layer into sand and gravel
Victoria Line Underground	London	1965	the shield was ineffective in supporting the overlying ground
Southend-on-sea Sewage Tunnel	UK	1966	Water inflow into the tunnel
Rørvikskaret Road Tunnel on Highway 19	Norway	1970	Bad design (weak ground)
Orange-fish Tunnel	South Africa	1970	Methane gas entered during excavation
Munich Underground	Germany	1980	Overstressing of the sprayed concrete
Holmestrand Road Tunnel	Norway	1981	Bad design, weak ground
Gibei Railway Tunnel	Romania	1985	Bad design (water inflow due to fine-grained sand above the crown)
Moda Collector Tunnel	Istanbul Sewerage Scheme. Turkey	1989	Bad design (soft clay)
Seoul Metro Line 5 - Phase 2	Korea	1991	Bad design
Seoul Metro Line 5 - Phase 2	Korea	1992	Bad design
Seoul Metro Line 5 - Phase 2	Korea	1993	Bad design
Munich Underground	Germany	1994	Bad design
Heathrow Express	UK	1994	Bad design, lack of quality control
Los Angeles Metro	USA	1995	Bad design
Motorway Tunnels	Austria	1993 - 1995	During construction
Docklands Light Rail	UK	1998	Bad design
Athens Metro	Greece	1991-1998	Bad design
Lærdal Road Tunnel on European Highway E 16	Norway	1999	During construction
Sewage Tunnel	Hull. UK	1999	Fluctuation of ground water
Taegu Metro	South Korea	2000	Fluctuation of ground water Overloading
Channel Tunnel Rail Link	UK	2003	During construction (vibration)
Météor Metro Tunnel	France	2003	

Tunnels	Location	Date	Reason
Oslofjord Subsea Tunnel	Norway	2003	Bad design for long term
Shanghai Metro	China	2003	During construction
Tunnel Failure	Japan	2003	During construction
Guangzhou Metro Line 3	China	2004	Natural hazard (rapid fluctuation of ground water)
Singapore MRT		2004	During construction, bad design
Kaoshiung Rapid Transit	Taiwan	2004	During construction (vibration)
Oslo Metro Tunnel	Norway	2004	During construction
Kaoshiung Rapid Transit	Taiwan	2004	Bad design
Hsuehshan Tunnel	Taiwan	1991-2004	Unexpected geology
Barcelona Metro	Spain	2005	During construction
Lausanne M2 Metro	Switzerland	2005	During construction
Lane Cove Tunnel	Australia	2005	Unexpected rock slippage
Kaoshiung Rapid Transit	Taiwan	2005	During construction
Nedre Romerike Water Treatment Plant Crude Water and Potable Water Tunnels	Norway	2005	Bad design (weak soil)
Hanekleiv Road Tunnel	Norway	2006	Bad design
Stormwater Management and Road Tunnel (SMART)	Malaysia	2003 – 2006	During construction
Sao Paulo Metro Station	Brazil	2007	During construction
Guangzhou Metro Line 5	China	2008	During construction
Langstaff Road Trunk Sewer	Canada	2008	During construction
Circle Line 4 Tunnel	Singapore	2008	During construction
Hangzhou Metro Tunnel	China	2008	During construction
Cologne North-South Metro Tram Line	German	2009	During construction
Brightwater Tunnel	USA	2009	During construction
Seattle's Beacon Hill Light Rail	USA	2009	During construction
Cairo Metro Tunnel	Egypt	2009	During construction

Tunnels	Location	Date	Reason
Shenzhen Express Rail Link		2011	During construction
Hengqin Tunnel	Macau	2012	Natural hazard (increase of groundwater) + weak ground

As it can be observed in the previous table, failures in tunnels can be clasified as failures that take place (1) during the construction process and (2) during their service life. The former is provoked mainly due to the limited previous studies of the field, lack of qualified workers and quality control during construction. The latter, is caused mainly due to bad design which does not take into account soil characteristics and uses inappropriate safety factors.

7.2 Industrial Infrastructures

MARS data indicates that approximately 60% of major hazard losses of containment incidents are related to technical integrity and, of those, 50% have ageing as a contributory factor. RIDDOR data has shown that between 1996 and 2008 it is estimated that there have been 173 losses of containment incidents that can be attributed to ageing plant mechanisms.

The main shared databases are listed in the table below :

Database	Organism	Area	Web site
The Analyse, Recherche et Information sur les Accidents (ARIA) database	MEDDE	France	http://www.aria.developpement-durable.gouv.fr/
The accident database	Icheme	Worldwide	www.icheme.org
The Major Accident Reporting System (MARS)	EC	Europe	https://emars.jrc.ec.europa.eu/
FACTS (failure an Accident Technical Information System)	TNO	Worldwide	www.tno.nl
HCR (Offshore Hydrocarbon Releases)	HSE	North Sea	http://www.hse.gov.uk/offshore/hydrocarbon.htm
MHIDAS (Majot Hazard Incident Data Service)	HSE	Worldwide	
PSID (Process Safety Incident Database)	CCPS	Members of the project	www.aiche.org/CCPS/ActiveProjects/PSID/index.aspx
RMP*info (Risk Management Program)	US EPA	US	
VICTOR	GESIP	France	http://www.gesip.com/index.php
WOAD (World Offshore Accident Database)	DNV	Worldwide (offshore)	www.dnv.fr
ZEMA (Central Reporting and Evaluation Office for Hazardous Incidents and Incidents in Process Engineering Facilities)	Umweltbundesamt	Germany	http://www.umweltbundesamt.de/nachhaltige-produktionanlagensicherheit-e/zema/index.html
JST – Failure Knowledge database	HATAMURA Institute	Japan	http://www.sozogaku.com/fkd/en/

Different major references for failure and incidents are also listed below:

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- A Review of High-Cost Chemical/Petrochemical Accidents Since Flixborough 1974, IchemE Loss Prevention Bulletin April 1998
- Loss Prevention Bulletin, various issues
- Hazardous Cargo Bulletin, various issues
- Large Property Damage Losses in the Hydrocarbon Chemical Industries – A Thirty Year Review, 2001
- The Costs of Accidents at Work, Health and Safety Executive, 1997
- 1999 Process Safety Performance Measurement Report, API
- Report on a Study of International Pipeline Accidents, Health and Safety Executive, CRR 294/2000

7.2.1 Statistical analysis per industry and event type

According to eMARS, and as can be seen in the following bar graph (see Figure 5), from years 2000 to 2012 chemical industry shows the highest rate of reported major accidents, followed by petrochemical and oil refineries, metal processing industries, wholesale and retail storage and distribution activities, plastic and rubber manufacturing processes, production and storage of pesticides, biocides and fungicides, waste treatment and disposal, metal processing industries using electrolytic or chemical processes and, finally, power supply and distribution businesses.

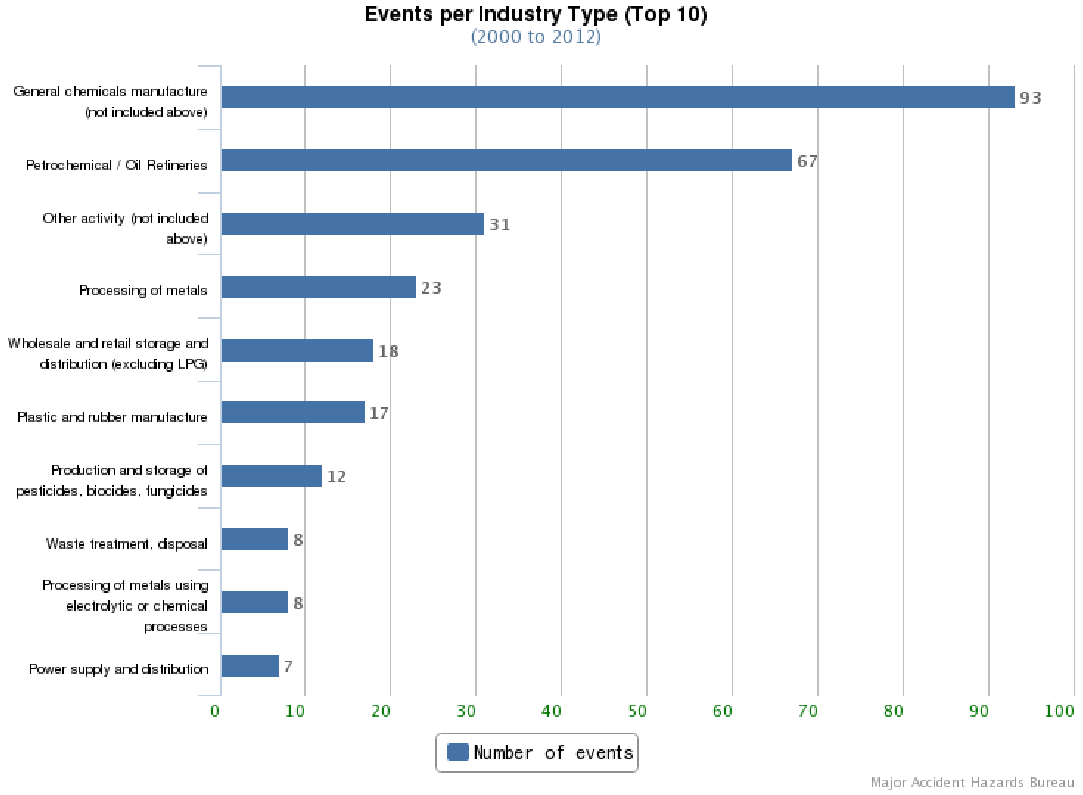


Figure 5: Top 10 of major accidents per industry type (2000 to 2012)

The number of reported major accidents classified per type of accident, during the period 2000 to 2012, can be seen in the following figure (see Figure 6). It can be appreciated that there is an important drop in the number of accidents; but still those caused by release activities are over accidents caused by fire, explosions and transport related tasks.

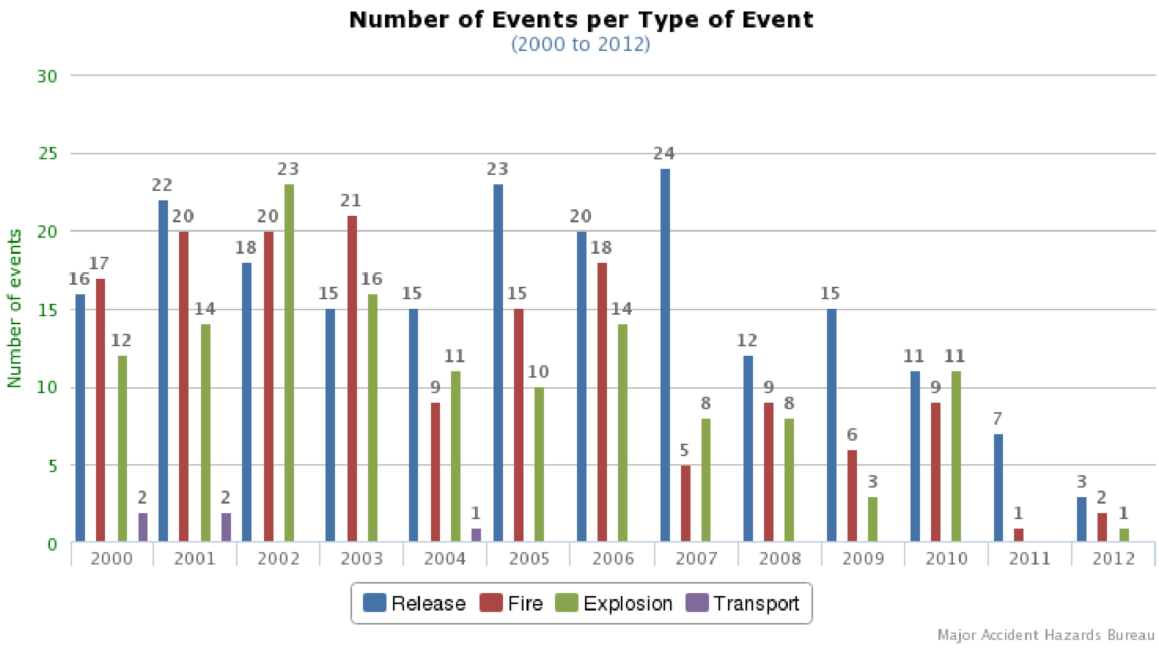
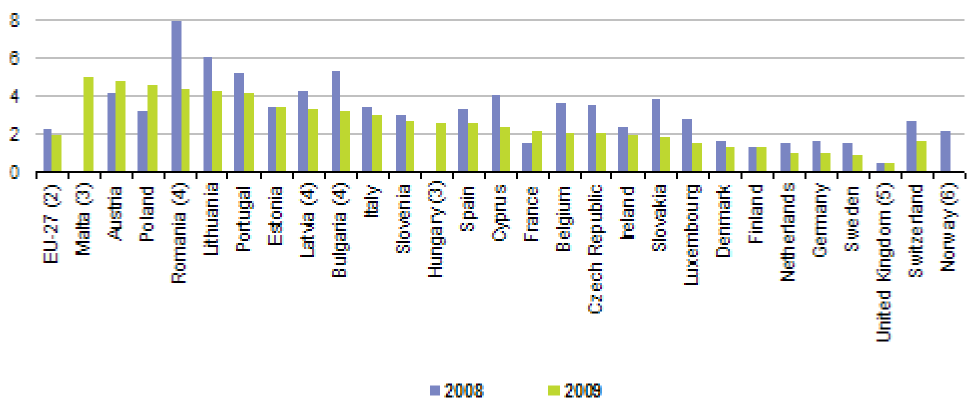


Figure 6: Number of major accidents per type (2000 to 2012)

The total number of fatal accidents at work (industrial plants) around the European Union has significantly dropped during last decade, mainly due to the adoption of safety standards and rules. For instance, and as established by the Eurostat, the number of fatal accidents from year 2008 to year 2009 is distributed as can be seen in the following bar chart (see Figure 3). The highest rate of incidences is located in the East part of Europe. Countries like Romania and Lithuania are on the top, followed by Portugal and Bulgaria; whereas the United Kingdom and Finland present the lowest rate of accidents.



(1) Greece, not available.
(2) Estimates exclude Greece and Northern Ireland; estimates include a certain level of under-reporting for Bulgaria, Latvia and Romania.
(3) 2008, not available.
(4) Data include a certain level of under-reporting.
(5) Great Britain (hence, excluding Northern Ireland); also excludes road traffic accidents at work.
(6) 2009, not available.
Source: Eurostat (online data code: hsw_n2_02)

Figure 7: Number of accidents at work, 2008 and 2009 (incidence rates per 100.000 people employed)

Despite the continuous fall of incidents over last years, the European Union has recently experienced a raised concern about the aging issue regarding the industrial infrastructures in use. This is mainly due to a series of accidents that are directly linked to aging machinery and structures that have recently occurred (i.e.: a total of 120 in the last 10 years in France with an increase of the frequency in the last years). Therefore, specific actions to deal with this issue (from both economical and safety perspectives) have been already launched by some Member States.Additionally, important civil infrastructures (i.e.: power plants, tunnels, bridges or railway systems) are reaching the end of their designed useful life time. In this context, several accidents due to aging have already occurred (i.e.: the collapse of bridge I-35 in Minneapolis in 2007), with huge economic impact and potential risk.

7.2.2 Statistical analysis for petrochemical industries

Following parts present several statistical analysis from HSE (2010) and INERIS (2009) respectively on the databases MARS and ARIA for petrochemical industies. About 294 accidents reports covering the period 1980 to 2006 from MARS and 300 reports covering the period 1999 to 2008 from ARIA database have been treated.

Both exploited database are :

- MARS (Europe): The Major Accident Reporting System (MARS) was established to handle the information on 'major accidents' submitted by Member States of the European Union to the European Commission in accordance with the provisions of the 'Seveso Directive'. Currently, MARS holds data on more than 700 major accidents since 1980. Circumstances, causes and consequences of accidents are furnished by inspectors of Member State of the European Union. Near accidents are also furnished on a voluntary basis by industrialists.
- ARIA (Worldwide) : The Analyse, Recherche et Information sur les Accidents (BARPI) database holds details of over 40000 accidents and incidents. This database first concerned classified installations and has been extended to transport of hazardous materials, gas collection and distribution , hydraulic work, mines, quarries and underground storage. Informations sources are french inspectors, press and professionnal or international organism.

Reports of accidents from refinery, oil depots, chemistry and production of gaz are studied in INERIS report (2009) and illustrated below. The analysis shows that about 33% of incidents due to ageing appearing in the ARIA database during the last 10 years concerns piping, due to the length of these equipments and the difficulties to inspect underground pipes.

A classification by activity sector has also been realized by INERIS (2009), and shows that most of the accidents come from the chemical industrie (about 45 %, see Figure 9). It can be explained by the presence of highly corrosive products.

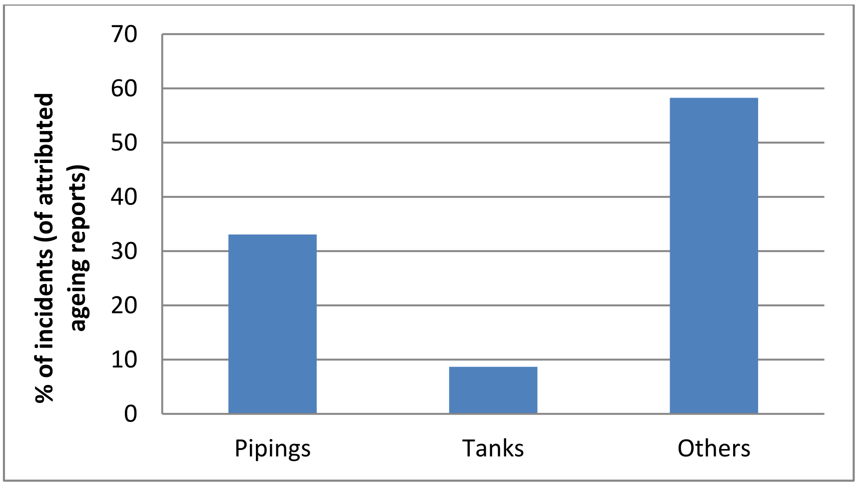


Figure 8 : Proportion of incident by equipment

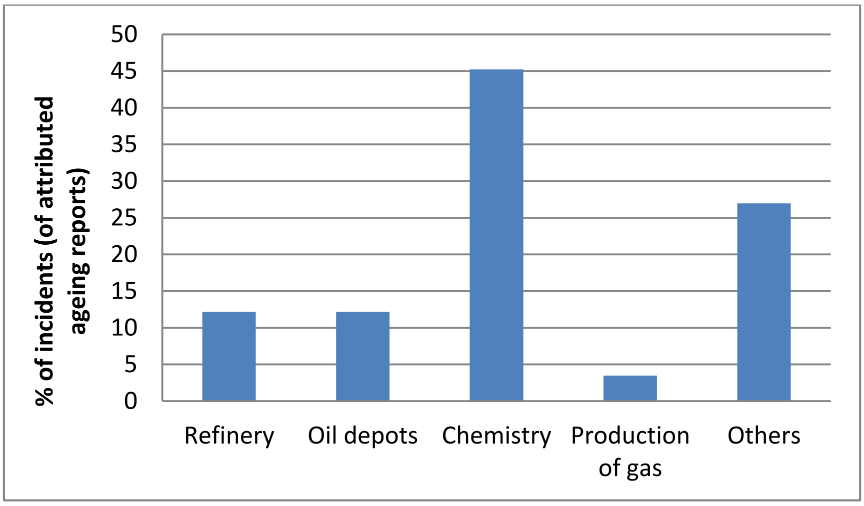


Figure 9 : proportion of incidents by activity as a fraction of attributed ageing reports

The analysis of INERIS (2009) only takes into account the accidents related to corrosion and fatigue in France. The number of accident in connection with corrosion is 117, whereas only 10 accidents are related to fatigue.

The analysis of causes made by HSE (Figure 10) shows that there are five corrosion accidents for each fatigue event. Since theses statistic doesn't take in account a very large number of accident in connection with fatigue (about 10 for ARIA and 14 for MARS), there is a quite good agreement between both analysis to qualify corrosion as the most important cause of incident.

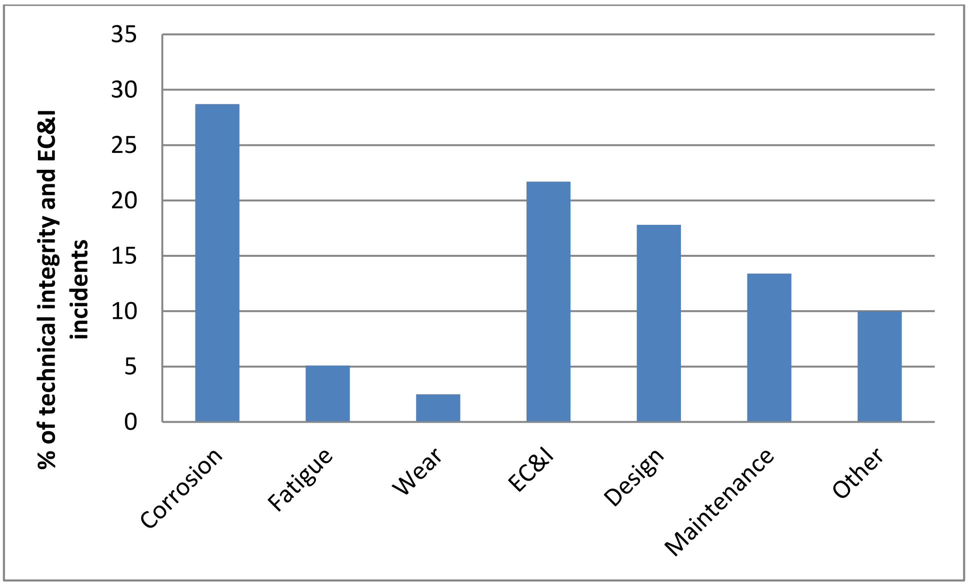


Figure 10 : Causes for loss of integrity in MARS data

The main root causes of corrosion accidents seems to be internal corrosion phenomena (by lack or absence of internal coating) and corrosion under insulation (INERIS, 2008).

Several ageing issues can lead to incidents. The number of reported incidents involving ageing of the MARS database is sufficient to produce graphical representation against the most common issues (Figure 11 : Part of ageing issue categories as a fraction of attributed ageing reportsFigure 11, HSE (2010)). The fact that the most common ageing issue concerns plant corrosion is in good agreement with the conclusions of the previous part.

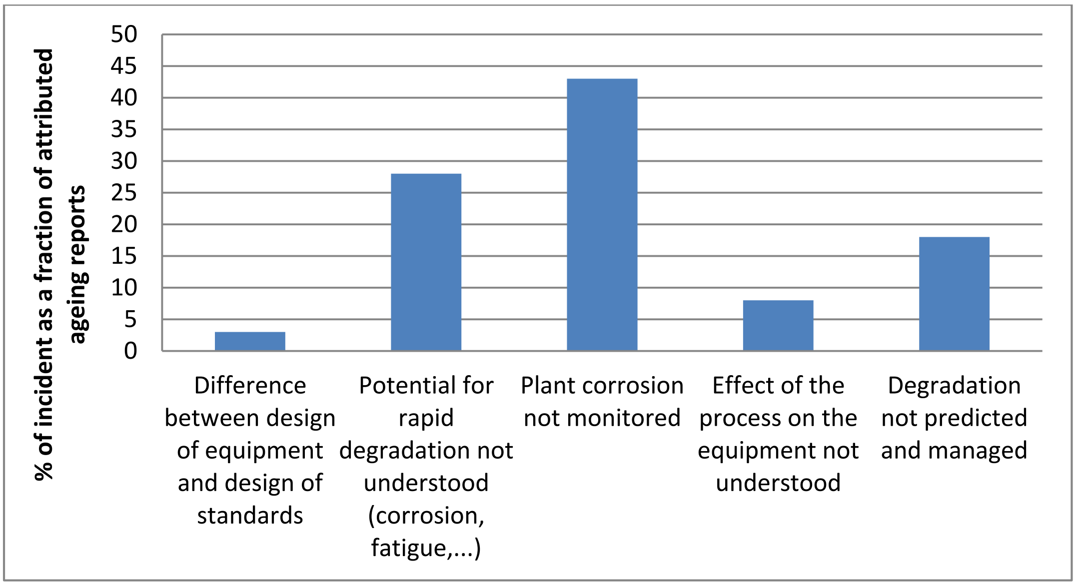


Figure 11 : Part of ageing issue categories as a fraction of attributed ageing reports

Several interesting observations are made by HSE (2010) in order to qualify how the plant ageing can be an issue:

1. The absolute number of incidents that can be directly attributable to plant ageing for primary containment systems is not insignificant. This is further focused by the observation from the MARS data that ageing issues appear to play a proportionately more significant role in major accidents when the reporting formats allow more positive identification.
2. There is general consistency between the incident reporting systems on the specific issues that are leading to failures on plant. Furthermore, the proportion of incidents attributed to the specific issues within each database is in good agreement.
3. Corrosion remains a significant issue.
4. Failure mechanisms that can lead to rapid failure but are still significantly influenced by age, e.g. fatigue, stress corrosion cracking, CUI etc, are a significant issue.
5. Planning of inspection and maintenance activities significantly influences the results, i.e. failure to plan for ageing issues is apparent in the databases.
6. The effect of the process on plant ageing is not fully understood, i.e. changing the process or increasing throughput is not evaluated in terms of the effect on the ageing rate.

These observations are in good agreement with those of INERIS (2009). This one underlines the fact that corrosion remains a significant issue, in particular for pipelines, which are difficult to inspect (buried or sheathed pipings, pipings in height on racks, thermally insulated pipings...).

8 Good Practices

Although Good Practices will be deeply analysied within Task T2.2 and Task 2.3, a brief introduction, mainly to Maintenance, will be carried out here.

Maintenance should be considered a fundamental pillar to face ageing effects in Transport and Industry infrastructures. Maintenance means "the work of keeping something in proper condition". In practice, the prevalent interpretation of maintenance is to "fix it when it breaks". This is a good definition for repair or correct a failure or damage, but not for maintenance. This is reactive maintenance. Proactive maintenance, or predict that something is going to occur before it really occurs and analyse the causes to avoid it in the future, is the mission.

8.1 Types of maintenace: philosophies&strategies

Four general basic types of maintenance philosophies or strategies can be identified, namely corrective/reactive, preventive, predictive and proactive maintenance. In practice, all these types are used in maintaining engineering systems. The challenge is to optimize the balance between them for maximum profitability.

For most infrastructures/plants, the best maintenance strategy combines several or all of these approaches. The appropriate combination will both affect and be affected by work processes, expertise, technology, and management.

The right mix will differ from plant to plant, as well as for different types of equipment. Generally, the more critical the process/infrastructure, the more the maintenance practices move toward predictive and proactive.

The fifth type of maintenance philosophies, reliability centered maintenance, employs the previous four techniques in an integrated manner to increase the probability that a machine or component will function in the required manner over its design life cycle with a minimum of maintenance. The goal of the philosophy is to provide the stated function of the facility, with the required reliability and availability at the lowest cost.

Next, the before mentioned maintenancephilosophiesare briefly described:

1. Corrective/reactive Maintenance: "run to failure"

Corrective maintenance refers to action only taken when a system or component failure has occurred. It is thus a retro-active strategy. The task of the maintenance team in this scenario is usually to effect repairs as soon as possible. Costs associated with corrective maintenance include repair costs, lost production and lost sales. To minimize the effects of lost production and speed up repairs, actions such as increasing the size of maintenance teams, the use of back-up systems and implementation of emergency procedures can be considered. Unfortunately, such measures are relatively costly and/or only effective in the short-term.

The implementation of other types of maintenance will reduce the need of corrective maintenance, but, for example, emergency actions due to different incidents are a type of corrective maintenance that cannot be avoided.

2. Preventive Maintenance: "time-based or cycle-based"

In preventive maintenance, equipment is repaired and serviced before failures occur. The frequency of maintenance activities is pre-determined by schedules. Preventive maintenance aims to eliminate unnecessary inspection and maintenance tasks, to implement additional maintenance tasks when and where needed and to focus efforts on the most critical items.

The higher the failure consequences are, the greater the level of preventive maintenance that is justified. This ultimately implies a trade-off between the cost of performing preventive maintenance and the cost to run the equipment to failure.

Inspection assumes a crucial role in preventive maintenance strategies. Components are essentially inspected at planned intervals, in order to identify needed action before failures actually occur. Preventive maintenance performed at regular intervals will usually results in reduced failure rates. As significant costs are involved in performing preventive maintenance, especially in terms of scheduled downtime, good planning is vital.

3. Predictive Maintenance: "condition-based"

Predictive maintenance refers to maintenance based on the actual condition of a component. Maintenance is not performed according to fixed preventive schedules but rather when a certain change in characteristics is noted. This strategy is based on monitoring and measuring the condition of the assets to determine whether they will fail during some future period and then take appropriate action to avoid the consequences of that failure.

Some of the resources required to perform predictive maintenance will be available from the reduction in breakdown maintenance and the increased utilization that results from pro-active planning and scheduling. Good record keeping is very important to identify repetitive problems, and the problem areas with the highest potential impact.

4. Proactive Maintenance: "root-cause"

Proactive maintenance is focused primarily on determining the root causes of a possible failure, and dealing with those issues before problems occur.

5. Reliability Centered Maintenance:

Reliability Centered Maintenance is the process that is used to determine the most effective approach to maintenance. It involves identifying actions that, when taken, will reduce the probability of failure and which are the most cost effective. It seeks the optimal mix of root-cause, condition-based, time-based and run-to-failure actions.

Initially developed by the aviation industry, RCM is rapidly becoming fundamental to the practice of maintenance management and is now in use at hundreds of industrial and service organizations around the world. It is defined by the technical standard SAE JA1011, Evaluation Criteria for RCM Processes.

After being created by the commercial aviation industry, RCM was adopted by the U.S. military (beginning in the mid-1970s) and by the U.S. commercial nuclear power industry (in the 1980s). It began to enter other commercial industries and fields in the early 1990s.

RCM involves the establishment or improvement of a maintenance program in the most cost-effective and technically feasible manner. It utilizes a systematic and structured approach that is based on the consequences of failure.

The principal features of each strategy are shown below their block in the next figure (see Figure 8):

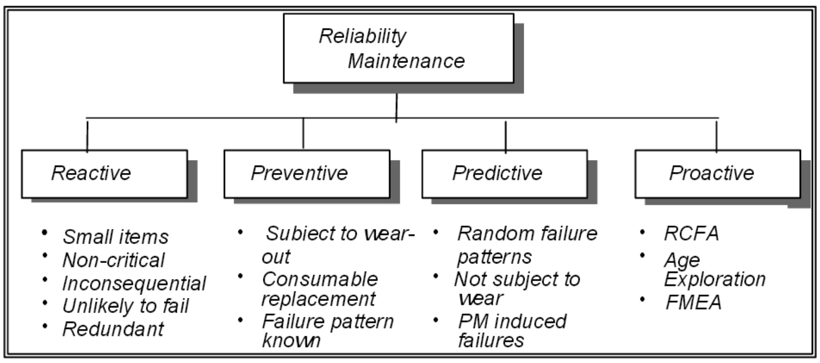


Figure 12: Reliability centered maintenance guide for facilities and collateral equipment, according to National Aeronautics and Space Administration.

All the above is summarized in the next table:

MAINTENANCE PHILOSOPHY	MAINTENANCE STRATEGY BASE	TECHNIQUE NEEDED
CORRECTIVE/REACTIVE	Run to failure	Emergency procedures
PREVENTIVE	Time /cycles	Periodic actions schedules
PREDICTIVE	Changes of the asset characteristics	Asset conditions monitoring
PROACTIVE	Root-cause	Failing sources detection
RELIABILITY CENTERED	Cost-effective and technically feasible maintenance program establishment	All the above

8.2 Maintenance procedures

The following will provide specific actions and methods to help develop a plan for executing infrastructures best maintenance practices that can make maintenance more efficient, reducing costs and improving reliability (as established by Ricky Smith, Life Cycle Engineering).

Best maintenance procedures are defined in two categories: standards and methods. Standards are the measurable performance levels of maintenance execution; actions and methods must be practiced in order to meet the standards.

8.2.1 Maintenance actions/methods

Condition based maintenance and planning for the implementation of best maintenance practices are essential. Smart monitoring, scheduling timelines, personnel assignments and documentation must be developed. The maintenance organization attributes should include:

- Maintenance skills training:

Performing a "job task analysis" will help define the skill levels required of maintenance employees. The JTA should be followed with a skills assessment of employee knowledge and skill levels.

The Analysis of the gap between required skills and available skills will determine the amount and level of training necessary to close the gap. Instituting a qualification and certification program to measure skills achievement will provide feedback on training effectiveness. It also will assist in resource allocation when scheduling maintenance tasks.

- Work flow analysis (organizational):

One element of the planning process that can be a major block is analyzing existing work flow patterns. A "computerized maintenance management system" will provide insights into organized, proactive work flow arrangements through its system modeling. Although you can tailor work flow and organizational attributes to match your plant's requirements, they still must work within any constraints imposed by the CMMS (Computerised Maintenance Management System).

- Condition monitoring and inspection:

When observing the condition of a particular system a set of monitoring devices and sensors have to be considered. Intelligent monitoring of equipment by means of sensors is essential in order to acquire relevant data, containing the characterization of failures and signs of deterioration in physical signals: acoustic and ultrasonic emissions, vibration analysis, accelerometers, current measurements, thermocouples, etc. [JLI95] [TSE01]. In addition to this data, environmental conditions, such as ambient temperature, pressure or humidity also provide very useful additional information [BRA11]. Inspection methods are also a key source of information to estimate the degradation of an asset; the most important are listed below:

- Visual and enhanced visual inspection
- Ultrasonic inspection
- Radiographic inspection
- Electromagnetic inspection
- Thermographic inspection

- Condition based maintenance:

Condition Based Maintenance (CBM) systems aim to anticipate a maintenance operation based on evidences of degradation and deviations from normal system behavior. In order to do so, relevant operational variables are monitored and specific Key Performance Indicators (KPIs) are calculated and analyzed to discover trends and knowledge of interest that can lead to a potential system failure. All available data is online processed, to provide a real time diagnosis. Smart sensing is a key issue in that concern. But the information is also gathered and stored for further analysis, taking into account heavier algorithms and calculations. Historical data are thus analyzed in order to infer a pattern or a signal trend that could lead to a failure. To this aim, several techniques and methods are adopted coming from different technological fields:

- Artificial Intelligence (AI)
- Statistical methods
- Signal processing techniques
- Similarity based methods (SBM)

When a diagnosis or a set of symptoms are detected or a deviation from normal operation is discovered, a maintenance procedure is launched.

- Computerized maintenance management system:

A CMMS is critical to an organized, efficient transition to a proactive maintenance approach, but don't forget GIGO (garbage in, garbage out) phenomenon, a computerindustryaxiom signifying that no matter how sophisticated an information processingsystem is, the quality of the information coming out of it cannot be better than the quality of the information that went in.

The CMMS output should be providing maintenance, engineering, operations or production, purchasing, and upper management with accurate and effective reports for evaluation and management.

- Work order system:

The types of work orders and organization needs will need to be defined. They will include categories such as planned/scheduled, corrective, emergency, etc. The work order will be the primary tool for managing labor resources and measuring the maintenance plan effectiveness.

- Procedural documentation:

Maintenance task documentation must be developed. Procedural documentation should include standardized listings of parts, materials, and consumable requirements; identification of the craft and skill levels required to perform the task; and stated frequencies or operating time-based period of performance. Categories of maintenance procedures that will be included in maintenance documentation:

- Routine labors (inspect, clean...)
- Replacements of minor or major components.
- Scheduled rebuilds or overhauls.
- Conditions monitoring procedures.

- Maintenanceengineering:

There must be a group whose responsibilities in this area should include evaluating preventive maintenance action effectiveness, developing predictive maintenance techniques and procedures, performing condition monitoring, providing planning and scheduling, conducting forensic investigations of failures including root cause analysis and evaluating training effectiveness.

- Establishment, assignment and training of a planner-scheduler:

The planner has diverse duties, must be familiar with the maintenance process, must be a good administrator and must have the appropriate level of authority to carry out his role. The following are typical responsibilities of the planner:

  - Develop maintenance program for each piece of equipment/structures.
  - Provide detailed job plan instructions/procedures.
  - Publish negotiated maintenance schedules.
  - Assist with development of periodic overhaul schedule.
  - Determine part requirements for planned jobs.
  - Arrange for special tools and equipment.
  - Provide necessary drawings/documents for jobs.
  - Ensure drawings/documents are revised and kept current.
  - Review equipment history for trends and recommend improvements.
  - Coordinate equipment downtime with production/use.
  - Provide cost information from equipment history.
  - Maintain equipment history in the CMMS as detailed and complete as possible.
  - Inform of job progress.
  - Establish equipment numbering system and number all equipment.
  - Ensure accuracy of equipment bills of materials.

Separation of planning from execution is a general rule of good management and good organizational structure.

- Maintenance inventory and purchasing integration:

The cost of inventory is almost always an area where cost reduction can be substantial. Begin by identifying the infrastructure/facility's parts, material and consumable requirements. All the inventory requirements data should be entered into the CMMS.

- Return on investment analysis:

Justification of anything today is based on cost. You will need to accumulate data on productivity, maintenance labor costs, maintenance material costs, inventory carrying costs, and reliability/availability data for at least 2 years prior to transition to the proactive maintenance organization.

Once you begin the planning and implementation of the changes, upgrades, etc., you will need to separate the development costs from the routine and normal operating costs of your facility to determine the total cost of implementing best maintenance practices.

When transition has been completed, accumulate the same cost and performance data that you obtained for the period prior to implementation. Obtaining this information must be planned for ahead of time so that you do not end up comparing apples and oranges and that you determine your real ROI.

- Evaluate and integrate use of contractors:

A final item to consider when incorporating best maintenance practices is integrating the use of contractors into your infrastructure/facility maintenance. Again it is necessary to determine costs for in-house performance and compare them to the costs of contracting out selected efforts. This likely will be a function of total facility size and operating costs.

8.2.2 Maintenance specific standards/guides

This section includes some international maintenance guides and standards.

- <u>MAINTENANCE GUIDES</u>

  - TRANSPORT INFRASTRUCTURE

Next, some guides from the Permanent International Association of Road Congresses (PIARC), an internationalforum for the discussion of all aspects of roads and road networks, are listed and described. They are classified according to the infrastructure they are referred to.

- Roads:

  - ✓ **Maintenance methods and strategies. PIARC 2013**: this report presents the results of the answers from 16 countries to a survey regarding improved maintenance methods for flexible and semi-rigid pavements and the maintenance strategies.Regarding improved maintenance methods, the variations in the answers were found to be large. It also became clear that the knowledge about the long-term performance of different maintenance methods varies. It is not always clear whether the durability is an "expected" durability or an "achieved" durability. Some case histories are described in appendix.In its second part, the report analyzes the existing strategies employed by the various agencies, drawing up a list of management indicators, and studying the changes made to these strategies over time. The environmental impacts after the implementation of changes were also considered. A second step consisted of analyzing the same information from the perspective of contracts involving partial or total outsourcing of works on the road network.

  - ✓ **Guide for maintenance of concrete roads. PIARC 2013**: the report firstly examines the different types of degradations of concrete pavements distinguishing those which are specific to jointed plain concrete pavements and those which relate to continuously reinforced concrete pavements. For each type of degradation, status indicator, status assessment, causes and remedial measures are presented.The report then describes the maintenance techniques providing precise indications on the products to use and the repair method. Three appendices complete the report: a survey on concrete pavements and the maintenance methods used world-wide; a case study of full-depth replacement of concrete panels with rapid strength concrete in California; a case study of rehabilitation of continuously reinforced concrete with high early strength concrete in South Africa.

  - ✓ **Road safety inspection guidelines for safety checks of existing roads. PIARC 2012**: a Road Safety Inspection (RSI) is a systematic, on site review, conducted by road safety expert(s), of an existing road or section of road to identify hazardous conditions, faults and deficiencies that may lead to serious accidents. After defining what is a road safety inspection, the report details what should be inspected, depending on the type of road and when should inspections be carried out. It provides a description of the inspection process: preparatory work in the office, field study, check lists, content of the inspection report and the remedial measures and follow up to be considered.The report addresses also the matter of who should carry out an inspection.

- Tunnels:

  - ✓ **Recommendations on management of maintenance and technical inspection of road tunnels PIARC 2012:** this report aims at presenting best practice for technical inspections as well as for the maintenance of equipment in road tunnels ranging from electromechanical systems to communication systems and operational devices.The scope, goal and types of maintenance are defined in Chapter 1.Chapter 2 presents advantages and drawbacks of a maintenance strategy based on preventive actions versus one based on a corrective approach. After deciding on the strategy of maintenance, the tunnel operator has to draw up a maintenance plan outlining all the tasks to be carried out, their frequency and other details on how to intervene. Dynamic and evolving over time, the maintenance plan will be the reference for all actions of maintenance done by internal staff or through subcontractors.Chapter 3 is dedicated to technical inspections. Methodology, areas to be covered, inspection plan, rating system, inspection report are presented comprehensively. A glossary as well as the 3 approaches to subcontracting work maintenance (tables) can be found in the appendix.

- Bridges:

- ✓ **Prioritisation of bridge rehabilitation works PIARC 2012:** the challenge in bridge management is to ensure that all bridges in a road network remain fit for their intended purpose over their design life and beyond at minimum life cycle cost. The bridge rehabilitation prioritisation process is part of the entire road infrastructure management task and bridge asset managers must seek a balance between the proposed performance targets and reasonable funding needs. This exercise must be conducted in the context of acceptable professional practice and community expectation of appropriate access standards and service function. This report investigates the current practises in network level prioritisation of bridge maintenance interventions. Nineteen countries provided answers to different survey questionnaires designed to elicit details of the Bridge Management Systems and the bridge rehabilitation processes. The report presents the answers together with guidelines for prioritisation of maintenance interventions.

- ✓ **Increase the durability and lifetime of existing bridges PIARC 2012:**the scope of this study is to present a library of examples on methods of minimizing the maintenance or repair cost or the traffic restrictions through increasing the durability and lifetime of existing bridges or structure components. 49 examples from Europe, Japan, New Zealand, North America and South Africa are presented. They cover all essential construction components (bridge decks, slabs, supports, etc.). The different causes of damage include insufficient design, detailing, construction, maintenance, and impact from traffic, fire, etc.Examples compare a traditional repair method with a new, alternative repair method for solving the same problem. The examples are complemented by recommendation for future design in order to avoid the detected damage.

- ✓ **Management of bridge stock PIARC 2012:** this report presents the results of a survey, to which 16 bridge operators from 11 countries responded, about the management of their bridge stock.The first set of questions deals with the nature of the bridge stock, the management programmes, and the funds allocated yearly for bridge management and inspection programmes.The second set of questions is related to the bridge management system (BMS) used: whether such a system is implemented; who is in charge of data management in the system; the required expertise and qualifications to manage the management system; whether the BMS is useful to set priorities for a maintenance programme.Lastly, the managers were surveyed on the existence of objectives set annually about the condition of bridge assets and what measures would be necessary in order to improve prioritization of projects.The report ends with recommendations, including the implementation of BMS based on risk analysis.

- ✓ **Inspector accreditation, non-destructive testing and condition assessment for bridges PIARC 2012:** in the area of bridge inspector accreditation, this report reviews and compares the characteristics and qualifications required in various countries. It provides information on training courses, how they are organized, the content of courses, and their duration in order to obtain accreditation as a bridge inspector and requalification on a periodical basis.The second part of the report is a comprehensive analysis of non-destructive testing methods used by the inspectors of structures. For concrete and steel structures, for cables, masonry and timber, the report presents, regarding the various aspects tested, the non-destructive testing methods that are applied, their advantages and disadvantages and recommends the most appropriate method.Lastly, the report describes bridge condition assessment methods: damage catalogues, condition rating methods, per element and overall bridge rating. The report also makes recommendations on the assessment procedures and the use of condition assessment ratings.

- ✓ **Large road bridges: management, assessment, inspection, innovative maintenance techniques PIARC 2011.** This report deals with the organisation of the management of large bridges, the monitoring systems used on large bridges and specific aspects of the maintenance. It is based on the answers received to a questionnaire disseminated through the World Road Association TC D3 members to owners and managers of large bridges. It describes the management organisation of 10 large bridges, located in several countries and representing different structural types: cable stayed bridge, suspension bridge, large steel truss of different shapes (arch, cantilever beam), large prestressed concrete box girder, steel or concrete beams.

- ✓ **Adaptation to climate change for bridges PIARC 2011:** climate change has now become a global issue of concern and it is for this reason that the World Road Association has incorporated it into the strategic themes for the term 2008-2011. Higher levels of carbon-dioxide as part of greenhouse gas emissions are being released resulting in heat being trapped in the atmosphere, which over time will result in a rise in the earth's air temperature. This rise in temperature will filter into the oceans causing sea water to expand and therefore raise sea levels. There are already signs of extreme weather occurring in certain parts of the world resulting in events like drought, heavy rainfall, flooding, typhoons and violent storms and in addition landslides, rock falls, mudflows, avalanches and glacier melting. The frequencies of some of these events are also increasing.

- INDUSTRIAL PLANTS

Maintenance guides for industrial plants assets are very dependant on the asset manufacturer and/or provider. There exist common principles of asset management that can be generally applied to all assets, but the degree of applicability within individual entities may differ. Thus, the main principles of asset management for maintenance are the following (Australian National Audit Office, 2010):

- asset acquisition, disposal and life-cycle management decisions are integrated into an entity's strategic and organisational planning;
- asset planning decisions are based on an evaluation of alternatives, which assesses risks and benefits, and applies the Company's business plan or the Government's core procurement principle of value for money across the asset's life-cycle;
- an effective control structure is established for asset management;
- accountability is established for asset condition, use and performance; and
- disposal decisions are based on analysis of the methods which achieve the best available net return.

Within this asset management strategy, the maintenance plan is usually composed of a variety of activities and core concepts that can be seen in the following figure (see Figure 8).

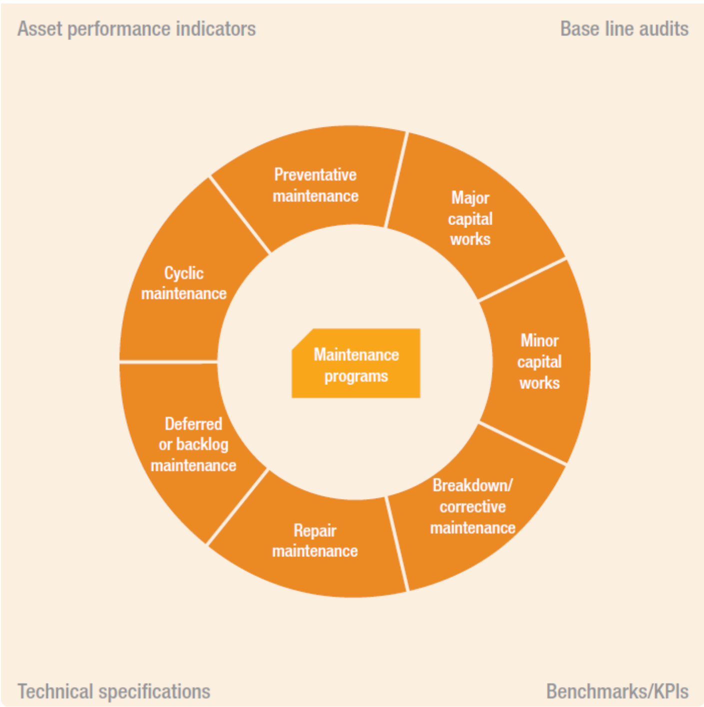


Figure 13: Common maintenance activities and core concepts for industrial assets

From a guidance perspective, planned maintenance can be preventive (based on periodic intervenctions), cyclic (based on planned life-cycle activities) and deferred or backlog (based on maintaining records of deferred maintenance to allow re-establishing the required level of maintenance). And with regards to unplanned maintenance, we can distinguish between repair (based on activities that are budgeted for, such as replacement of assets or componets) and corrective or breakdown strategies (based on activities that are not budgeted for, such as specific and unexpected failures during the theorical operational life of the asset). Unplanned activities are usually expensive and have a high impact in the business activity of the company, with direct implications in safety aspects; that is the reason way a lot of efforts are being made to minimise their occurrence.

Another interesting concept when identifying maintenance programmes for industrial plant assets is capital works. Major capital works, for instance, are regular planned capital works that intend to enhance the performance of existing assets, increasing their functionality or their useful life. Minor capital works, by contrast, are planned or unplanned capital works with less complexity and value, just used to enhance the asset's capabilities.

As an example of maintenance plan for a generic industrial plant asset and component, the normal set of activities could start by an overview of the general situation, then checking the required maintenance standard, then analyzing the specific maintenance requirements and the contract management and finally performing the monitoring and inspection for finding possible causes and most suitable fixing strategy.

These main principles can be applied to the industrial structures envisaged in present study:

- Primary containment systmes (Process and Utilities)
- Control & mitigation measures
- EC&I systems
- Structures

▪ <u>MAINTENANCE STANDARS</u>

ASTM is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services.ASTM International has no role in requiring or enforcing compliance with its standards. The standards, however, may become mandatory when referenced by an external contract, corporation, or government.

- In the United States, ASTM standards have been adopted, by incorporation or by reference, in many federal, state, and municipal government regulations. The National Technology Transfer and Advancement Act, passed in 1995, requires the federal government to use privately developed consensus standards whenever possible. The Act reflects what had long been recommended as best practice within the federal government.
- Other governments (local and worldwide) also have referenced ASTM standards
- Corporations doing international business may choose to reference an ASTM standard.

The standards produced by ASTM International fall into six categories:

- the Standard Specification, that defines the requirements to be satisfied by subject of the standard.
- the Standard Test Method, that defines the way a test is performed and the precision of the result. The result of the test may be used to assess compliance with a Standard Specification.
- the Standard Practice, that defines a sequence of operations that, unlike a Standard Test Method, does not produce a result.
- the Standard Guide, that provides an organized collection of information or series of options that does not recommend a specific course of action.
- the Standard Classification, that provides an arrangement or division of materials, products, systems, or services into groups based on similar characteristics such as origin, composition, properties, or use.
- the Terminology Standard, that provides agreed definitions of terms used in the other standards.

9 Conclusions

As discussed in this document, most important ageing concerns related to transport and industry are those that have a higher impact in terms of structural damage and potential risks. There exist some common ageing mechanisms that in practice equally affect to both transport infrastructure and industrial components, with slight differences, such as those caused by mechanical and thermal damage,. Nevertheless, there are some processes which are domain specific , for instance, those caused by sea water or chemical processes, which require special attention. As it has been analysed in this document, in order to prevent failures, special attention must be paid to the design phase, since a poor design and construction quality, as well as the lack of preliminary studies can lead to major disasters during construction phase and service life. In addition to this, failures during the service life are mainly caused by lack of maintenance, poor quality of construction and natural hazards. The latter cannot be avoided but the former are important issues that can be prevented, which would improve infrastructures ageing behaviour.

Maintenance actions and standards to be adopted in order to mitigate ageing effects have been enhanced and improved over last decades. Advanced monitoring and inspection techniques, which allow an important increase in asset related knowledge, are being investigated and developed. Therefore, in almost any transport infrastructure and industrial component it can be find a more or less complex maintenance procedure that aims to minimize the ageing effect and the impact of any unexpected, critical and/or risky behavior of the asset being monitored. However, the efficiency and reliability of estimations made (why, when and where something is going to fail, with what probability and what severity), is still a hot topic that requires a lot of efforts and study yet to be fully accomplished within these sectors.

Main challenges regarding ageing mechanisms are thus focused on establishing and applying the correct preventive actions to automatically deal with ageing problem. To do so, maintenance standards, techniques and good practices must be adopted. Therefore, an optimal RUL management of the infrastructures can be achieved by reinforcing the RAMS (Realiability, Availability, Maintainability and Safety) concept, which will allow mitigating the ageing effect and enlarging the useful life of the infrastructure.

Thus, in summary, the following challenges have been highlighted as the most relevant:

- Damage assessment methods and existing metrics for aging.
- Mitigation practices.
- Common intersecting issues among infrastructures to be utilized for better efficiency in improving safety and reducing costs.
- Decisionmaking procedures in managing retrofitting and prioritizing infrastructure (on different levels). Limitations and advantages.
- Specific hazards that afflict aging infrastructure (deterioration, sustainability, energy, obsolescence, wear and tear, etc.) and manmade hazards.

The challenges should be aimed at enabling an extension of the useful life-time of aged infrastructures:

- favoring component rather than full systems replacement and
- introducing sophisticated cost, risk, performance and resource analysis through the new Strategic Assets Lifecycle Value Optimization
- Better aligning infrastructure investments with economic development goals

- Increasing importance of the role of:
    - emerging engineering paradigms (performance-based considerations, resiliency, multihazards, etc.)
    - advanced technologies (superior materials, advanced systems, increased redundancies, etc.).
    - information Technologies such as monitoring.

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