Ageing management and monitoring of critical equipment in petrochemical applications: an Italian case study

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Abstract: Over the years, environmental health and safety issues have seen an ever-growing interest developed becoming a crucial and strategic aspect of today's business operations. Companies have focused efforts and resources on tasks, techniques, and rules to guarantee high protection level of health and safety at work according to national and international laws. In 2015, Legislative Decree No. 105, was issued in Italy, implementing the Directive 2012/18/EU on the control of major accident hazards involving dangerous substances. This Directive made clear the obligation to adopt a risk monitoring and control plan associated with the aging and corrosion of plants and equipment by operators of industrial plants. In this context, this work proposes a methodology, consisting of a structured approach, aimed at identifying the factors that have an impact on ageing process of industrial devices. In the first step, the root causes that can accelerate or retard the deterioration and damage process associated with time in service have been defined through an ageing fishbone (AFB) approach. In the second step, the effects of these factors have been assessed through a specific tool index-based by considering a rewards and penalties model. This methodology is applied to the critical equipment operating in the Mild Hydrocracking unit of a refinery located in southern Sardinia (Italy). The results show the practical applicability of an effective and easy to implement aging management tool aimed at ensuring safety and reliability of the equipment in a real use-case. Simplicity and relatively easy physical interpretation of the criticalities allow managing all potential aging effects resulting in key aspects to support the risk-based analysis.

Keywords: Equipment ageing, Major accident hazard, Industrial safety, Fish-bone analysis, Seveso

1.Introduction

In recent decades, health and safety issue has been long recognised becoming a basic pillar in the industrial context. Indeed, the prevention of major accidents has been the main concern to companies that have directed their efforts on improving safety at work according to national and international laws. The Seveso III Directive (Legislative Decree No. 105), which has been issued in the Italian National legislations since 2015 (Eu Council, 2012), provides a common framework for the control of risk related to major accident hazards. One of the most important requirements within the Directive concerns the management program for safe ageing of critical equipment implemented in Seveso plants. Increased awareness on the importance of plant ageing has raised the attention of researchers, regulators, and practitioners depending on two main reasons: (i) most of the industrial base assets in Europe have largely exceeded their design lifetime, therefore, they are at risk from age-related deterioration and damage (Milazzo and Bragatto, 2019); (ii) an accurate analysis of major industrial accidents occurred in recent years evidenced their close correlation with ageing issue (Fabiano and Currò, 2012; Wood *et al.*, 2013; De Rademaeker *et al.*, 2014; OECD, 2017). In this scenario, the introduction of a plan for the safe management of ageing is emerged as a key aspect aimed at both monitoring the condition of equipment and assessing the deterioration mechanisms. Indeed, the concept of ageing is not referred to how old an equipment is, but it concerns its condition and how this gradually varies over time due to deterioration or damage effects that increase the likelihood of failure during operating lifetime (Wintle et al., 2006). Since companies aim to maximise the life of their plants and to replace as few machinery as possible, the ageing management should be cost effective, nonetheless, it must primarily ensure safety of people, equipment and the environmental. To this end, plan maintenance, inspection and periodic monitoring of the equipment should be performed to detect status condition aimed at preserving their integrity and functionality. A number of studies on this topic have been proposed in literature based on different perspectives. (Milazzo and Bragatto, 2019) proposed a framework for assessing the ageing of critical equipment at Seveso plants by considering both monitoring and inspection tasks. (Krivanek and Fiedler, 2017) analysed the ageing effect on nuclear power plant structures, machinery and equipment. (Bragatto et al., 2020a) integrated an ontological approach into the decision-making process for the implementation of control and monitoring critical equipment ageing at Seveso plants, while (Vairo et al., 2018) implemented a safety management systems aimed a defining a reliable procedure for critical element identification. (Mansfield et al., 2012; Milazzo et al., 2018) illustrated the ageing mechanisms could generate a major accident. (Bragatto et al., 2020b) and (Ancione et al., 2020) proposed a short-cut methodology based on ageing fishbone (AFB) approach and a Bayesian network-based approach to assess ageing issues at Seveso plants, respectively. (Bragatto and Milazzo, 2016; Candreva and

Houari, 2013) presented a guideline for risk-based inspection (RBI) aimed at supporting the assessment of the factors that affect the ageing issue at Seveso plants. (Gyenes and Wood, 2016) analysed the root causes of the major chemical accident that occurred over the past 50 years by considering the databases provided by the Major Accident Hazards Bureau of the European Commission's Joint Research Centre (JRC), while (Kieskamp et al., 2019) limited that analysis to the cases occurred in Netherlands. Hence, even though existing literature outline the impact of ageing management on risk-based analysis and the importance of the inspection technique on proper decision-making process, available information on root-causes that influence ageing are limited (Ancione et al., 2020). Therefore, this paper aims to propose a methodology to identify the main factors affecting the ageing process in Seveso facilities through a systematic approach based on ageing fishbone (AFB) tool. Then, an overall ageing index is introduced to assess the impact of the accelerating or retarding factors on ageing aimed at supporting intervention/inspection decisions. Particularly, this analysis is applied to the critical equipment operating in the Mild Hydrocracking unit of a refinery located in southern Sardinia (Italy). The remainder of this paper is organized as follows: in Section 1, the discussion of ageing management within Seveso plants is reported; Section 2 illustrates the methodology based on AFB and the index-based classification approach; Section 3 presented the achieved results, while in conclusions and future researches are depicted in Section 4.

2.Ageing within Seveso plants

In Europe, the Directive 2012/18/EU (Seveso III) addresses the ageing issue through the implementation of plans and activities aimed at ensuring the integrity of critical components at major hazard establishments. It requires their operator to implement a Safety Report (SR) based on risk assessment analysis. In the process industry, other valuables practices are the asset management ISO55000 (Milanese et al., 2017), the risk-based approach presented by (Bragatto et al., 2012), and plant lifecycle management (PLM) (Candreva and Houari, 2013). Particularly, in Oil&Gas and petrochemical industry, the traditional inspection methodology is the Risk-Based Inspection (RBI) practice developed from standard codes, as API 580/581 RBI (API American Petroleum Institute, 2016a, 2016b). RBI refers to the application of risk analysis principles based on the identification of the associated risk level of assets aimed at managing and optimizing proper inspection plans. However, this approach is characterized by a significant constraint resulting in a lack of clear guidelines. Indeed, since it does not cover several industries that are classified as major accident hazard under the Seveso legislation, subjective content could be introduced in the failure modes identification and related probabilities (Milazzo and Aven, 2012). Moreover, RBI is based on a semi-qualitative risk assessment consisting of the probability analysis of the failure and its consequences, while Seveso Directive involves a quantitative analysis consisting of evaluating the probability of potential events and a simulation process on the release and the impact of scenarios. The Seveso Directive also requires periodic mandatory inspections of the monitored systems. Those are carried out by the Competent Authorities that have the consistency of all the tasks and activities adopted by the company to postpone as long as possible the effects of deterioration mechanisms. Therefore, the Seveso Directive is widely considered as a landmark for legislation in most countries for industrial accident policy. In this context, the implementation of a proper ageing management practice involves three different processes able to provide a clear picture of the equipment: (i) the learning process for acquiring appropriate knowledge of the deterioration mechanisms that affect the equipment during its operating time; (ii) the information acquisition process based on history-taking information gathering by considering each change made during whole lifetime; (iii) the data acquisition process based on the data obtained from monitoring of equipment integrity, functionality, and reliability (Zio, 2016). These three processes drive from a strategic point of view the intervention or replacement decisions according to the health status of damaged or deteriorated equipment. Indeed, the main goal is to extend their in-service life as long as possible by taking into consideration both concepts of safety and costs reduction.

3.Ageing management methodology

The Seveso III Directive establishes that the ageing issue of critical equipment has to be assessed by an auditor on behalf of the owner or the Competent Authorities. Hence, the role of that auditor is to define the suitability of all the activities to manage and delay as possible, the effects of deterioration mechanisms performed by the company. In this context is framed the proposed methodology based on an ageing fishbone (AFB) model proposed by (Bragatto and Milazzo, 2016) that has been adopted by the National Competent Authority for the application of the Seveso Directive due it is considered as a quick tool to visualize and categorize deterioration factors. It is a short-cut method based on cause-and-effect diagram used to identify the potential causes involved in the ageing issue assessment (Milazzo and Bragatto, 2019). This technique relies on these assumptions generally adopted in process manufacturing (Reason, 1997): (i) operating condition and physical environment affect the protective layers that machinery are equipped with; (ii) failures, stops and damages are affected by human and organizational factors that lead to deficiencies in the technical and operational preventive layers. Hence, the equipment ageing is determined by considering accelerating and retarding factors and, each of these factors is scored in terms of a penalty or compensation. The achieved scores are evaluated for each factor by considering a four-level scale, i.e. from 1, which represents the lowest value, to 4 that represents the maximum value. Positive values are assigned to compensation, while negative ones to penalty. Then, an overall index is achieved combining the average score of accelerating factors (ageing index) and the one of retarding factors (longevity index). Thus, the overall index is used by regulators as a support for the assessment of the ageing management plans' adequacy. Generally, if this index is not satisfactory, several actions need to be taken as (i) the identification of proactive tasks to prevent ageing issue and design/operational mitigation protection layers; (ii) a continuous effort to identify all the potential deterioration mechanisms; (iii) the setting of a proper plan to handle potential consequences of failures (Vairo et al., 2018). The proposed methodology allows to assess ageing issue through a qualitative approach but it has several important strengths: (i) the proportionality between the adopted scores and the resulting prevention actions is ensured; (ii) the freedom of choice amongst various alternative approaches (Risk Based, Condition Based, Life Cycle) since it is not affected by the inspection policy type; (iii) it is a visual tool easy to use and it provides a rapid ranking of findings; (iv) it consists in uniform criteria that can be repeated on all plants under Seveso Directive. Nevertheless, as other index methods, this method presents some weaknesses, such as (i) lack of depth that could oversimplify the complex relationships of deterioration mechanisms and (ii) it provides only a static view of the audit.

The accelerating factors are evaluated during a reference period equal to at least 10 years (to be significant), and they are categorized as follows:

Age/In-service time: it is defined as the ratio between the actual age and the expected one:

$$F_{Age} = \frac{Actual\ Age}{Expected\ Age}$$

Or, it can be defined as the ratio between actual operating hours and the maximum allowed in-service hours.

Stops: it is defined as the ratio between the number of unplanned stops and the total number of stops over a reference period.

$$F_{Stops} = \frac{Unplanned\ Stops}{Total\ Stops}$$

Failures: it is defined as the ratio between the actual number of failures over a specific period and the number of expected failures according to the generic failure rates established in the Safety Reports as required by Seveso Directive:

$$F_{Failures} = \frac{Actual\ failures}{Total\ failures}$$

Accidents/Near-misses: it is defined as the ratio between the number of accidents and near-misses related to ageing issue and the total number of occurred events over a reference period.

$$F_{Accidents} = \frac{Accidents\ and\ Near\_Misses}{Total\ Events}$$

Damages: it is defined as the ratio between the number of severe damages that occurred and the total number of critical items over a reference period.

$$F_{Damages} = \frac{Severe\ Damages}{Critical\ Items}$$

Deterioration mechanisms: it involves the different physical and chemical mechanisms considered as the basis of deterioration. This factor consists of the average value obtained from combining three scores which are (i) the ability to detect the mechanisms, (ii) the propagation velocity of the deterioration process, and (iii) the consequences of it. Seveso Directive reports a comprehensive list of the potential deterioration mechanisms and the corresponding score based on the three factors mentioned. Table 1 reports the criteria to assign the scores to each accelerating factor.

Table 1: Accelerating factors for ageing management

Factor	Criteria	Score
Age/In-service time	$F_{Age} \leq 90\%$	1
	$90\% < F_{Age} \leq 100\%$	2
	$100\% < F_{Age} \leq 125\%$	3
	$F_{Age} > 125\%$	4
Stops	$F_{stops} \leq 10\%$	1
	$10\% < F_{stops} \leq 25\%$	2
	$25\% < F_{Stops} \leq 60\%$	3
	$F_{Stops} > 60\%$	4
Failures	$F_{Failures} < 0.5$	1
	$0.5 \leq F_{Failures} < 1$	2
	$1 \leq F_{Failures} < 2$	3
	$F_{Failures} \geq 2$	4
Accidents/Near-misses	$F_{Accidents} < 5\%$	1
	$5\% \leq F_{Accidents} < 15\%$	2
	$15\% \leq F_{Accidents} < 35\%$	3
	$F_{Accidents} \geq 35\%$	4
Damages	$F_{Damages} \leq 1\%$	1
	$1\% < F_{Damages} \leq 3\%$	2
	$3\% \leq F_{Damages} \leq 5\%$	3
	$F_{Damages} > 5\%$	4
Deterioration mechanisms	The average score is accounted for (i) ability to detect mechanisms, (ii) propagation velocity, and (iii) consequences (see Table 2)	1,2,3,4

Table 2: Deterioration mechanisms and their scores

Deterioration mechanisms	Detec.	Prop. velocity	Conseq.	Score
Long.term metallurgy	4	1	4	3
Short-term metallurgy	4	4	4	4
Uniform thinning	4	3	4	3
Local thinning (corrosion/erosion)	2	2	3	2
Corrosion due to soil/ambient	1	1	2	1
Stress corrosion cracking	4	2	4	3
Damage from hydrogen at high temperature	4	3	4	4
Fatigue	3	3	4	3
Creep	3	3	3	3

Corrosion under insulation	4	3	4	4

The retarding factors, that aims to contrast the ageing process, are categorized as follows:

Integrity management system: it is defined as the performance level assessed by considering the integration between the inspection practices for critical items and the Safety Management Systems (SMS or SGS-PIR as reported in Italian Seveso Directive).

SMS audit: it is the average value obtained by the combination of the scores related to the number of major and minor non-conformity points reported in the SMS audit for major accident prevention.

$$F_{Audit,max} = \frac{Major\ non-conf.}{Total\ points\ SMS\ audit}$$

$$F_{Audit,min} = \frac{Minor\ non-conf.}{Total\ points\ SMS\ audit}$$

$$F_{Audit,tot} = mean(F_{Audit,max}, F_{Audit,min})$$

Inspection results: it considers the combination of the scores achieved from inspection planning and the results of integrity and functionality tests carried out on critical items.

$$F_{Insp,func} = \frac{Good\ results\ item\ functionality\ test}{Total\ item\ functionality\ test}$$

$$F_{Insp,integ} = \frac{Good\ results\ item\ integrity\ test}{Total\ item\ integrity\ test}$$

$$F_{Insp,plan} = \frac{Inspection}{Total\ Inspection\ Planned}$$

Adequacy control: it considers the efficiency of inspection by involving the combination of two scores, the extension, and the degree of adequacy of both practices and qualification of inspectors.

Process control: it considers the performance level of the process control system adopted to monitor process parameters such as pressure, temperature, mass flow, etc.

Physical protection and covering: it considers the adoption of protective systems as cladding, lining, coating, cathodic protection, etc. and it is calculated as the average value of the scores achieved from the frequency of the controls and the actual condition of the protective system adopted.

Table 3 reports the criteria to assign the scores to each retarding factor.

Table 3: Retarding factors for ageing management

Factor	Criteria			Score
Integrity management system	Compliant			1
	Partial integrated			2
	Total integrated			3
	Risk-based			4
SMS audit	$F_{Audit,min}$	$F_{Audit,max}$		
	30%	20%		1
	20%	10%		2
	10%	5%		3
	5%	3%		4
Inspection results	$F_{In,func}$	$F_{In,integ}$	$F_{In,plan}$	
	<90%	<98%	<90%	1
	90÷95%	98÷99%	90÷95%	2
	95÷98%	99÷99.5%	95÷99%	3
	>98%	>99.5%	>99%	4
Adequacy control	The average score is accounted for (i) extension and (ii) adequacy of inspection and inspectors			1,2,3,4
Process control	Unregistering local control system			1
	Control system with data recording			2
	Control system with data recording and automatic blockage			3
	Control system with data recording, automatic blockage, and certified blockage			4
Physical protection and covering	Controls frequency	Protection's conditions		
	Low	Poor		1
	Medium	Medium		2
	High	Good		3
	Very High	Perfect		4

Figure 1 reports the fishbone diagram according to the different factors analysed. Therefore, the average scores achieved for accelerating and retarding factors are used to evaluate the overall value of penalties and compensations. These values are expressed as the ageing index (I_a) and the longevity index (I_l) respectively. Finally, the overall adequacy index ($I_{Overall}$) is assessed as the sum of the ageing and longevity index as:

$$I_{Overall} = I_a + I_l$$

A positive value of $I_{Overall}$ depict the adequacy of the practices and the activities adopted for ageing management. On the other hand, its negative value suggests an improvement in the technical and managerial solutions aimed at increasing the scores according to the retarding factors.

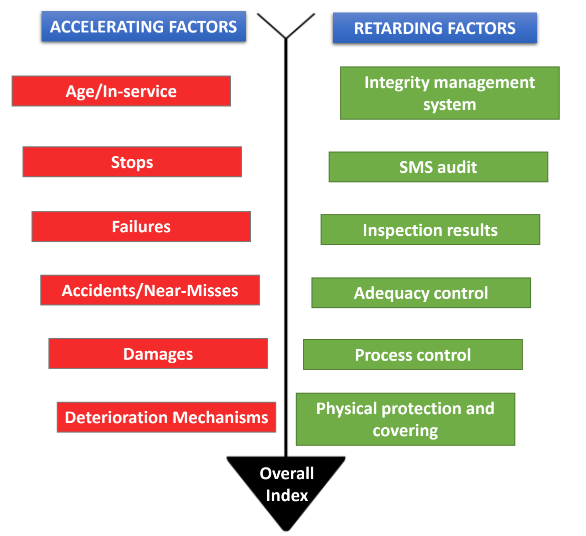

Figure 1: Factors included in the ageing fishbone diagram

4.Case Study

The case study presented in this work is referred to an ageing management process applied to mild hydrocracking

(MHC) unit as part of a refinery located in Sardinia (Italy). In general, Hydrocracking (HC) is a catalytic refining process widely used to remove sulfur and other undesired compounds from petroleum products such as naphtha, gasoline, diesel fuel, kerosene, and fuel oil. It is a two-stage process that combines catalytic cracking and hydrogenation: a bi-functional catalyst able to rearrange and break hydrocarbon chains, as well as adding hydrogen to aromatics and olefins, is employed aimed at producing naphthenes and alkanes. The main goal is to split the molecules of the feed into lighter molecules having higher average volatility and economic value such as jet fuel, diesel, relatively high-octane rating gasoline fractions, and LPG (liquefied petroleum gas). In mild hydrocracking, the process is run at less severe operating conditions similar to those of a vacuum gas oil desulfurizer. It involves the conversion of vacuum gas oil to significant yields of lighter products with a consequent savings of hydrogen since it operates at almost half of the hydrogen pressure used in conventional hydrocracking (Fahim et al., 2009).

4.1 Ageing management for MHC unit

The overall adequacy index $I_{Overall}$ is assessed by investigating the potential root causes of ageing process. The accelerating and retarding factors are examined and derived taking into consideration the process flow diagram of the MHC unit, experts' experience from plant operators, and reports from inspections. Therefore, the cause and effect relationships among these factors and the actual condition of the different equipment analysed are achieved through both a priori knowledge and system observation. The main criticalities that emerged in MHC unit are:

- Leakage from makeup flanged connection of the centrifugal compressor that could involve the releasing of hydrogen into the atmosphere by dispersion or jet-fire. Since a number of this item is considered equal to 15 in the entire plan, the frequency of this event is estimated to $f = 1.3 \cdot 10^{-4}\, event/year$.
- Feed leakage from flange and piping due to thermal shock deriving from the simultaneous presence of the heating fluid and the absence of the heated fluid. This can lead to break gaskets of the flange with the consequent risk of fire, dispersion, or jet-fire. Since a number of this item is considered equal to 35 in the entire plan, the frequency of this event is estimated to $f = 3 \cdot 10^{-4}\, event/year$.
- Leakage due to failed pipelines/flanges deriving from embrittlement or acid corrosion. This can lead to dispersion into the atmosphere or jet-fire. According to the different stage of the MHC unit, the frequency of this event is estimated to $f = 1.55 \cdot 10^{-5}\, event/year$ for 1/4" pipe size and $f = 1.36 \cdot 10^{-5}\, event/year$ for 1" pipe size for stage characterized by high H_2S content while, $f = 6.95 \cdot 10^{-6}\, event/year$ for 1/4" pipe size and $f = 5.97 \cdot 10^{-6}\, event/year$ for 1" pipe size for the stage characterized by the presence of H_2 and H_2S. Finally, in this last stage, since a number of leakage due to failed flanges is considered equal to 75, the frequency of this event is estimated to $f = 6.6 \cdot 10^{-4}\, event/year$.
- Leakage for pumps seal due to absence/poor maintenance activities, wear and lack or fault during the pump start. This can be led to the realising of diesel, H_2 or H_2S, dispersion, fire, or jet-fire. Since in the MHC unit, 10 pumps are adopted, the frequency of this event is estimated to $f = 1.4 \cdot 10^{-2}\, event/year$.
- Leakage from gas-recirculating compressor flanges leading to the realising of H_2 from seals or flanges, dispersion into atmosphere or jet-fire. Since a number of this item is considered equal to 15 in the entire plan, the frequency of this event is estimated to $f = 1.3 \cdot 10^{-4}\, event/year$.

Therefore, starting from this information, the P&IDs (piping and instrumentation diagrams) are analysed aimed at identifying all the equipment affected by the potential root-causes described above (rotational items such as pumps and compressors, are not taken into consideration as reported in Seveso Directive).

5.Results

Once criticalities and the affected equipment are detected, the values of each accelerating and retarding factor are assessed in the reference period. In tables 4 and 5, the different methodologies considered to evaluate these factors are reported for each one.

Table 4: Methods to evaluate the accelerating factors

Accel. Factors	Description
Age/In-Service Time	It is evaluated by introducing corrosion rate as the ratio between the thickness decrease and the interval of detection
Stops	The unplanned stops occurred during work operation are assessed by considering: (i) maintenance history reporting; (ii) planned stop reporting (cleaning, ordinary maintenance…); (iii) Solomon's refining studies (as refining benchmarking).
Failures	The expected failures are assessed by considering failure rates from Safety Report. However, no failures have been detected.
Accidents/Near misses	The number of accidents related to the deterioration of critical equipment is considered. Only one accident has been detected but its causes are not the results of deterioration phenomena
Damages	One severe damage has been recorded leading to the functionality reduction of the production process. A sudden detachment of the shut-off

	valve occurred in the delivery line of the compressor.
Deterioration mechanisms	The deterioration phenomena are assessed as reported in RBI Directive. The mechanisms identified are thinning, stress corrosion cracking (SCC) and external damage due to corrosion under insulation (CUI). Thus, this factor is calculated according to the score reported in table 2.

Table 5: Methods to evaluate the retarding factors

Retar. Factors	Description
Integrity Management System	It is assessed according to the performance level of the inspection practices integrated into the Safety Management Systems
SMS audit	In the reference period, the examined points were 54. Minor non-conformity points identified are related to recommendations for improvement while, major non-conformity ones are related to detection during inspections and to specific corrective actions.
Inspection results	The Palladio Inspection Manager suite is adopted with the purpose of documenting operational activities carried out during inspections
Adequacy control	Several inspective techniques are used as visual inspection, ultrasonic thickness measurement, liquid penetrate inspection, magnetoscopic testing to detect the different deterioration mechanisms. For these, the following values are considered: F_{extens}= 0.46, F_{thinn}= 0.50, F_{CUI}=0.50, F_{SCC}=0.5. According to the qualification of inspectors, a score of 3.5 is selected as the average value of score performed by a similar refinery. Therefore, this factor is assessed by considering the mean between the sum of different deterioration mechanisms factors and the qualification of inspectors one.
Process control	Since performance level of the process control system is high, the score of 4 is selected.
Physical protection and covering	Palladio Inspection Manager suite is adopted to define the score for two types of covering techniques, (i) cladding, and (ii) coating

Table 6 summarizes the scores of the different factors analysed, by considering both accelerating and retarding ones. The algebraic sum of the scores achieved to accelerating and retarding factors is adopted to assess the overall ageing index of the Mild Hydrocraking system.

This metric is positive, and it is equal to:

$$I_{Overall} = 1.19$$

Table 6: Summary of ageing factors

Accel. Factors	Score	Retar. Factors	Score
Age/In-Service Time	1.49	Integrity Management System	4.00
Stops	4.00	SMS audit	2.00
Failures	1.00	Inspection results	3.33
Accidents/Near misses	1.00	Adequacy control	2.78
Damages	2.00	Process control	4.00
Deterioration mechanisms	2.86	Physical protection and covering	3.36
TOT	2.06	TOT	3.25

This result shows that the current ageing management is adequate. However, improvement can be achieved by reducing the accelerating factors and, consequently, by increasing the score of retarding factors. Indeed, among the accelerating factors, the lowest score refers to the unexpected stops thus, a proper maintenance policy should be implemented to ensure both an increase of the availability and a reduction of system failures. On the other hand, concerning retarding process, the lowest score is related to the adequacy control thus, an appropriate planning inspection should be introduced aimed at improving the efficiency of both practices and qualification of inspectors.

6.Conclusions

This study presents a structured approach for the identification of the factors that have an impact on ageing process of the critical equipment operating in the Mild Hydrocracking unit of a refinery located in southern Sardinia (Italy). Through an ageing fishbone (AFB) model, an overall index is assessed resulting from a proper analysis of accelerating or retarding factors affecting the deterioration and damage process associated with time in service. The results show a positive score of the overall ageing index thus, the current ageing management is appropriate. However, improvement concerning the lowest scores achieved in both accelerating and retarding factors should be tackled aimed at increasing the reliability and the safety of systems and operators as well as refining the planning inspection in terms of suitable practices and qualification of inspectors. Generally, the scenario proposed in this work is framed into the idea that the safety management must consider the importance of maintenance and inspections to prevent accidents aimed at ensuring the safety and reliability of the equipment. To the end, the practical applicability of an effective and easy to implement ageing management tool, as AFB, allows: (i) providing valid support by useful information to help practitioners in the decision-making process concerning ageing management and risk-based analysis; (ii) providing the inspectors making decisions during on-site inspections a systematic data collection on equipment ageing at Seveso plants.

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References

Ancione, G., Bragatto, P., Milazzo, M.F. (2020). A Bayesian network-based approach for the assessment and management of ageing in major hazard establishments. *Journal of Loss Prevention in the Process Industries* 64.

API American Petroleum Institute (2016)a. Risk-based Inspection. *API recommended practice API RP* 580. Washington, D.C., US.

API American Petroleum Institute (2016)b. Risk-Based Inspection Methodology. *API recommended practice API RP 581*. Washington, D.C., US.

Bragatto, P., Milazzo, M.F. (2016). Risk due to the ageing of equipment: Assessment and management. *Chemical Engineering Transactions* 53, pp. 253–258.

Bragatto, P., Site, C.D., Faragnoli, A. (2012). Opportunities and threats of risk based inspections: The new italian legislation on pressure equipment inspection. *Chemical Engineering Transactions* 26, pp. 177–182.

Bragatto, P.A., Ansaldi, S.M., Agnello, P., Di Condina, T., Zanzotto, F.M., Milazzo, M.F. (2020)a. Ageing management and monitoring of critical equipment at Seveso sites: An ontological approach. *Journal of Loss Prevention in the Process Industries* 66.

Bragatto, P.A., Pirone, A., Vallerotonda, M.R., Milazzo, M.F. (2020)b. Safety report updating for aged seveso plants. *Chemical Engineering Transactions* 82, pp. 13–18.

Candreva, F., Houari, M. (2013). Plant Screening for Ageing Impact in the Process Industry. *Chemical Engineering Transactions* 31, pp. 253–258.

De Rademaeker, E., Suter, G., Pasman, H.J., Fabiano, B. (2014). A review of the past, present and future of the European loss prevention and safety promotion in the process industries. *Process Safety and Environmental Protection* 92, pp. 280–291.

Eu Council (2012). Directive 2012/18/EU on the control of major-accident hazards involving dangerous substances. *Official Journal of the European Union L197*.

Fabiano, B., Currò, F. (2012). From a survey on accidents in the downstream oil industry to the development of a detailed near-miss reporting system. *Process Safety and Environmental Protection* 90, pp. 357–367.

Fahim, M., Al-Sahhaf, T., Elkilani, A. (2009). *Fundamentals of Petroleum Refining*, 1st Editio. ed. Elsevier Science & Technology Books.

Gyenes, Z., Wood, M.H. (2016). Lessons learned from major accidents relating to ageing of chemical plants. *Chemical Engineering Transactions* 48, pp. 733–738.

Kieskamp, K.K., Heezen, P.A.M., Geus, E.C.J. (2019). Ageing (- Seveso installations) in the Netherlands. *Chemical Engineering Transactions* 77, pp. 415–420.

Krivanek, R., Fiedler, J. (2017). Main deficiencies and corrective measures of nuclear power plants in ageing management for safe long term operation. *Nuclear Engineering and Design* 323, pp. 78–83.

Mansfield, D., Atkinson, T., Worsley, J. (2012). The importance of recognising and managing ageing plant. *Institution of Chemical Engineers Symposium Series* 823, pp. 425–433.

Milanese, S., Salvador, E., Decadri, S., Ratti, R. (2017). Asset integrity management system (aims) for the reduction of industrial risks. *Chemical Engineering Transactions* 57, pp. 283–288.

Milazzo, M.F., Ancione, G., Scionti, G., Bragatto, P.A. (2018). Assessment and management of ageing of critical equipment at seveso sites. *Safety and Reliability - Safe Societies in a Changing World - Proceedings of the 28th International European Safety and Reliability Conference, ESREL 2018*, pp.1629–1636.

Milazzo, M.F., Aven, T. (2012). An extended risk assessment approach for chemical plants applied to a study related to pipe ruptures. *Reliability Engineering and System Safety* 99, pp. 183–192.

Milazzo, M.F., Bragatto, P. (2019). A framework addressing a safe ageing management in complex industrial sites: The Italian experience in «Seveso» establishments. *Journal of Loss Prevention in the Process Industries* 58, (70–81).

OECD, Organisation for Economic Cooperation and Development (2017). Ageing of Hazardous Installations. *OECD Environment, Health and Safety Publications*, Series on Chemical Accidents no. 29.

Vairo, T., Reverberi, A.P., Milazzo, M.F., Fabiano, B. (2018). Ageing and creeping management in major accident plants according to seveso III directive. *Chemical Engineering Transactions* 67, pp. 403–408.

Wintle, J., Moore, P., Henry, N., Smalley, S., Amphlett, G. (2006). Plant ageing Management of equipment containing hazardous fluids or pressure. *Health and Safety Executive Research Report RR509*, UK.

Wood, M.H., Lisa, A., Arellano, V., Van Wijk, L. (2013). Corrosion-Related Accidents in Petroleum Refineries: Lessons learned from accidents in EU and OECD countries. *European Commission, Joint Research Centre*, Luxembourg: Publications Office of the European Union.

Zio, E. (2016). Some Challenges and Opportunities in Reliability Engineering. *IEEE Transactions on Reliability* 65, pp. 1769–1782.