CHEMICAL ENGINEERING TRANSACTIONS
VOL. 67, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Valerio Cozzani, Bruno Fabiano, Davide Manca

ISBN 978-88-95608-64-8; **ISSN** 2283-9216

Ageing Assessment and Management at Major-Hazard Industries

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As a consequence of the obligations of the Directive Seveso III, there is a need of methods and tools that support industrial managers and the auditors, respectively, to manage and to verify the ageing status of critical equipment. Risk-Based Inspection methods (RBI) are usually used, as well as some other recommended practices (ASME, API or RIMAP). Criticalities are associated with RBI methods as these were born to optimise inspections' costs by comparing them with safety levels, thus an effort is always necessary to adapt the method in order to manage ageing. This work describes an under-development system that supports industrial managers and auditors in controlling and managing ageing. It can be considered as a *virtual sensor*, made up by hardware and software. It collects information about process variables (recorded by control systems), external variables, inspection information and other data, then it processes collected information and predicts the numeric value of a performance indicator based on the approach for the ageing assessment, which was developed by an Italian working group on ageing. Based on such an indicator the prediction of the ageing state of the equipment is possible as well as its management based on the levels of industrial risk acceptance. The software is a dynamic model indicating factors that accelerate and those that slow down the degradation processes. The model is expected to build a "digital twin" of a complex plant by using a huge amount of data, which is valuable to understand how the plant will age in the next future.

1. Introduction

Ageing of equipment and facilities in the process industries has become a relevant issue in recent years. The problem is particularly recognised in Europe, where industrial sites have a century of life and to build new plants appears very difficult, given scarce available resources as well as difficulties in obtaining the authorisation due to very congested lands. A few national regulators, designed for the implementation of the EU Directives for the prevention of chemical accidents, have recognised the relevance of this issue over the last ten years and more. The first one was the British Competent Authority (HSE), which published in 2006 the guideline for the safe management of ageing plants under the COMAH regulation (Wintle et al., 2006). According to the HSE's report, the first step to manage aged plants is the awareness that ageing is not about how old the equipment is but is about what is known about its condition and the factors that influence the onset, evolution and mitigation of its degradation; this means that ageing management is a process that starts at the time of the facility's installation. The importance of the ageing phenomenon was definitely recognised in 2012, when the Directive UE/2012/18 (Seveso III) was published. It imposes the plant manager to adopt a plan to control the hazard related to ageing and corrosion (art.8 Annex III point b.iii) and the inspectors to verify the adequateness of the activities planned by the plant management to guarantee a safe ageing (art. 20). Thus, managers have the obligation to demonstrate the adequateness of the management of such an issue. The application of the newest Directive in EU countries started in 2015.
The huge impact of an inadequate management of ageing on workers' safety, industrial assets and environment has been clearly demonstrated in technical and scientific literature. Indeed, the EU Commission published an exhaustive report about corrosion-related accidents in the refineries (Wood et al., 2013), whereas the OECD reported about accidents collected in all process industries (OECD, 2017); other investigations that evidences the relevance of the occurrence of accidents due to ageing are given by De

Rademaeker et al. (2014) and Fabiano and Currò (2012). Detailed analyses of accidents, associated with the unsafe management of aged equipment in chemical industries, are due to Semmler (2016) and Gyenes and Wood (2016). As discussed at the ESReDa seminar in 2006, it is essential to discriminate between the material degradation, due to deterioration mechanisms (e.g. corrosion, erosion, fatigue) and that compromise the features of the system, and the obsolescence. The latter term refers to changes in the working context (e.g. technical, economic and regulatory aspects) and makes the system no longer acceptable, even though it is still in good condition. Another issue to be accounted for is the organisational ageing, which is the inadequate capability of organisation to follow changes over time.

This paper focuses on material degradation and, partially, on organisational ageing; whereas the obsolescence is definitely out of the scope of the proposed approach discussed below. In this study, the ageing of individual piece of equipment is a “finite” problem, which involves just corrosion science experts, whereas the ageing of a process plant includes thousands of items and is a much more complex problem that involves organisation, resources, procedures, regulation and standard codes. Whilst there are thousands of papers on different deterioration mechanisms and related control techniques, there are much less documents discussing the overall management of ageing of facilities. As discussed by Bragatto et al. (2017), the management of this phenomenon is based on three pillars: (i) a sound knowledge of physical and chemical degradation mechanisms, (ii) a careful management of information along the plant lifecycle and (iii) an effective and continuous measurements of process variables in order to provide an adequate amount of useful data.

Currently, Risk-Based Inspection methods (RBI) are common used approaches and recommended practices are ASME, API or RIMAP, even if criticalities are associated with RBI methods as these were born to optimise inspections’ costs by comparing them with safety levels, thus an effort is always necessary to adapt them to ageing management due to several reasons.

The objective of this paper is to overcome the limit of static method for ageing assessment and management with the aim to develop a more suitable model, based on the assessment of accelerating and retarding factors, which is expected to be included in a dynamic tool.

2. The fishbone approach for ageing management at Seveso establishments

Beyond the most popular methods for ageing assessment and management, other approaches include: (i) asset management according to ISO 55000, discussed by Milanese et al., 2017, (ii) the plant lifecycle management PLM approach, integrated with a score based on leading and lagging indicators, discussed by Candreva and Houari (2013), and (iii) the risk-based approach, discussed by Bragatto et. al. (2012). In these three papers, the issue of safe ageing at process plants is analysed from the point of view of the industrial manager, who has to make decisions about the equipment life extension or decommissioning as well as about inspections and maintenance planners. After the Directive Seveso III, the issue of ageing has to be analysed also from the point of view of the auditor, which has, on behalf of the owner or the Competent Authorities, the duty to understand in a very short time the adequateness of the activities performed to delay, as long as possible, the effects of deterioration mechanisms. Bragatto et al. (2016) developed an approach (named *fishbone method*) for auditing the ageing management at Seveso establishments that is an index method, including penalties for ageing accelerating factors and compensations for ageing retarding ones (Figure 1). Accelerating factors include age/in-service time, deterioration mechanisms, defects/damages, failures, stops and accidents/near-misses; whereas retarding factors include safety management system (SMS), audits SMS, adequacy controls, inspection results, process control and physical protections. In 2018, the National Committee for the application of Seveso Directive, according to art. 20 of Directive UE/2012/18, adopted the method to be applied for inspections at Seveso in Italy; an extensive testing phase of the method will be conducted during the whole 2018, which allows collecting opinions about its applications and its criticalities.

The strengths of the fishbone approach are the following:

1. a proportionality is guaranteed, i.e. control measures are always proportionated to the strength of deterioration mechanisms and the actual equipment conditions;
2. the method does not depend on the inspection policy type, therefore, the operator is free to choose amongst various alternative approaches (Risk Based, Condition Based, Life Cycle).

Nevertheless, as other index methods, the approach has some weaknesses, which can be summarised in the following points:

1. its application is very quick and many details could be overlooked, attention should be paid in order to not miss such details;
2. it is not a dynamic approach, as it provides just a shot at the audit time.

The objective of the paper is to go beyond the limits of such a quick method, tailored for regulatory inspections, and develop a model suitable for internal audit. It is assumed the internal audits are more frequent and detailed than those made by the operator (safety executive), therefore, the basic idea is to achieve the actual evaluation of accelerating and retarding factors aiming to develop a much more dynamic tool.

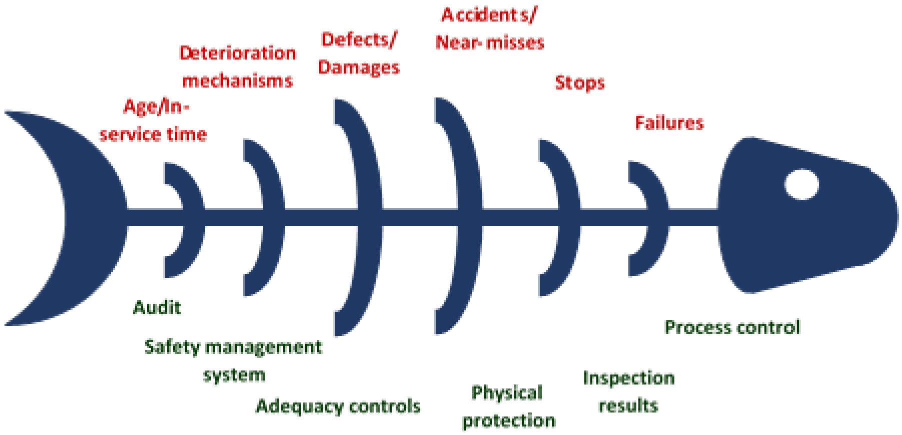

Figure 1: Fishbone model (Bragatto et al., 2016).

The capability of measuring the actual plant conditions and foreseeing the future ones have been included in the previous listed key factors by means of the use of a simple Bayesian network or Belief Network. The core of the paper is the dynamic model of the collected factors acting onto the ageing process. The dynamic model is suitable to be implemented into a digital representation. By feeding the digital model with adequate data, it is possible to achieve a continuous monitoring of the actual ageing condition and potential evolution, essential for a dynamic management of ageing.

2.1 Implementation of the fishbone in a Belief Network

In general, a Belief Network allows representing causal relationships of a domain of variables. Its main properties are: (i) set of nodes and a set of directed edges between nodes, (ii) each node has a finite set of mutually exclusive states, (iii) the node coupled with the directed edges constructs a directed acyclic graph and (iv) each node A with respect to its parents nodes (B_1, B_2 , …, B_n) has an associated conditional probability table $P(A|B_1, B_2, …, B_n)$, in case the node A does not have parents, it is associated with an unconditional probability P(A). In this kind of representation, each node has discrete states that it can take and the node probability at each state, given the states of its parents, is defined by using a *Conditional Probability Table* (CPT) (Yavuz et al. 2006). The approaches to solve a BN problem vary according to the system's knowledge. There are four classes of learning for BNs from data:

1. Known structure and observable variables
2. Unknown structure and observable variables
3. Known structure and unobservable variables
4. Unknown structure and unobservable variables.

By using data from the fishbone model and some other collected during the testing phase, which began in 2018 in the whole Italian territory, the BN was solved with the first modality of learning.
According to the the fishbone, each ageing factor can be assessed by assigning a score that varies amongst four levels (states). Such states are defined as: 1 = low, 2 = medium, 3 = medium-high and 4 = high. Compensation factors are marked by a positive sign and concur to calculate the *ageing resistance* (range between +1 ÷ +4), whereas accelerating ones are marked with a negative sign and are related to the *ageing propension* (range between -1 ÷ -4). The sum of ageing propension and ageing resistance is a score representing the *overall adequacy* with respect the ageing phenomenon. As shown by Bragatto et al. (2017), some factors take into account sub-factors, these are assigned with an average value calculated from the score associated with related sub-factors.

3. Case Studies

The fishbone model has been applied to four establishments and data collected has been used to start learning the belief network. Table 1 reports the scores attributed to each factor and for each establishment during the verification of the equipment ageing status. The first step was a classification of equipment according to their typology. Then, the software Netica (Norsys website) has been used to build the network related to the fishbone model of Figure 1 and to calculate the overall adequacy. The following step was to assign a uniform distribution to the probability of each ageing factor.

Table 1: Scores attributed to each ageing factor during the testing phase

Factor	Plant 1 (LPG warehouse)	Plant 2 (Refinery)	Plant 3 (Tank Farm)	Plant 4 (Tank Farm)
Age/In-service time	Mature	Old	Mature	Young
Deterioration mechanisms	Level 2	Level 3	Level 2	Level 2
Defects/Damages	High	Medium	Medium	Insignificant
Accidents/Near-misses	Probable	Probable	Possible	Remote
Stops	Small	Small	Insignificant	Insignificant
Failures (LoC)	High probable	High probable	Remote	Probable
Safety Management System	Compliant with legislation	Integrated with RBI planning	Integrated with RBI planning	Integrated with RBI planning
Audit SMS	Medium	Medium	Medium	High
Inspection results	Level 4	Level 3	Level 2	Level 3
Adequacy controls	Level 3	Level 3	Level 3	Level 4
Physical protections	Good	Medium	Good	Good
Process control	With automatic blockage	Certificated	With automatic blockage	With automatic blockage

4. Results and discussion

The Belief Network representing the fishbone model is shown in Figure 2, where the nodes (variables of interest) have been created with respect to each ageing factor. In the same figure the probability distribution is given for each factor, for both the ageing propension and resistance and for the overall adequacy.

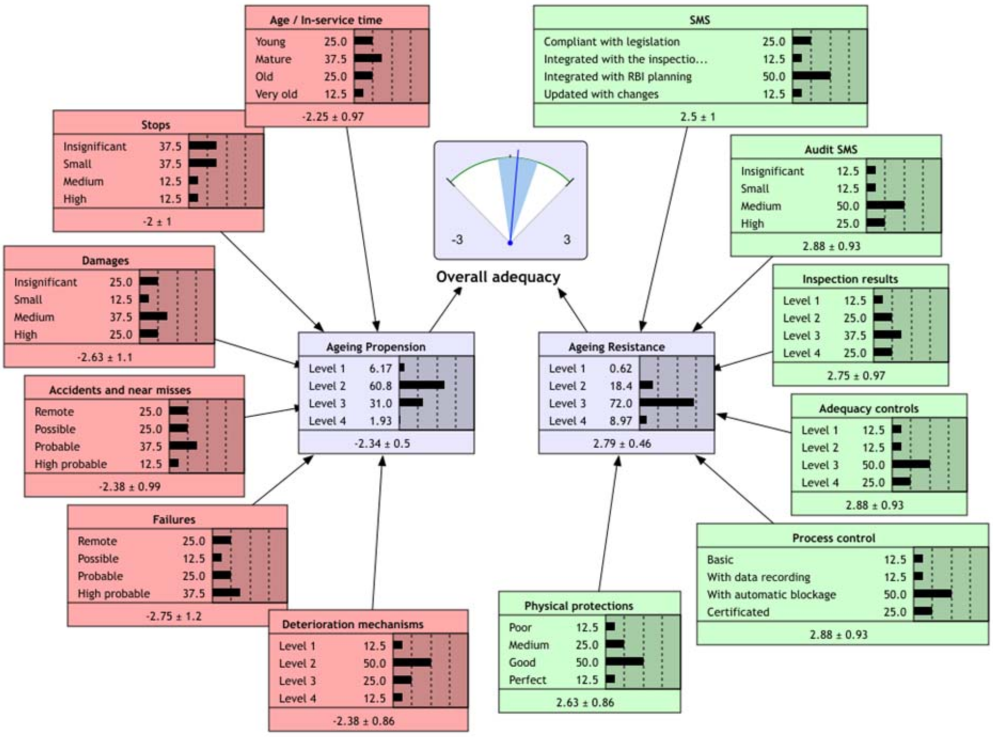

Figure 2: Implemented BN for the fishbone model

To obtain such distributions, the Belief Network had to learn from collected data for the case-studies, i.e. it had to learn the CPTs referred to each node of the net. This example shows simply how the net works, obviously to have a more realistic statistical distribution, more tests have to be done, their results are necessary to robustly estimate ageing propension and resistance and, then, to compare results.

4.1 Virtual sensor

The ageing model described in Section 1 does not take into account the relationships amongst accelerating and retarding factors that have been investigated by Milazzo et al. (2018). It is currently implemented in a software for the ageing monitoring and control at major hazard establishments and recalls completely the basic model. It represents the first version of the software, which will be part of a system called virtual sensor, which is under developed within the activity of the project SmartBench and will include also a hardware part. The final version of the model will include a more complex BN which will account for the relationships amongst factors.

Even if the static model appears the most appropriate for auditors acting on behalf of Seveso Authorities, the whole system will be properly designed to evaluate and update the status of critical equipment by accounting for data of most recent inspection. A dynamic model could be even more effective for industrial managers, especially when information about process variables, external data, inspection information and etc. are continuously collected and processed, in order to provide an overall picture of the system's status in a form of an index (overall ageing score). In this case the index allows the real-time forecasting of the equipment deterioration process and its management based on the industrial risk acceptance levels. Based on this model, a *digital twin* of a complex plant can be built, by integrating sensors and other smart devices collecting information from the equipment and the establishment.

Therefore, the *digital twin* is made up of measured data, managed information and models for the physical evolution of equipment. It simulates the real evolution of equipment, anticipating possible failures. This set of "data-information-knowledge" can be recalled from every "location" (e.g. cloud, DCS, etc.) through a device that constitutes the interface with the user.

5. Conclusions

In this work a more advanced version of the software (second release), which is part an under-development *virtual sensor* that supports industrial managers and auditors in controlling and managing ageing, is described. The current version collects information and predicts the numeric values of performance indicators based on the approach for the ageing assessment, which was developed by an Italian working group on ageing. The software is a dynamic model indicating factors that accelerate and those that slow down the degradation processes.

Due to the legislation requirement, in the context of major hazard establishments, inspections planning and maintenance activities are essential elements to guarantee a safe ageing of installations. These must be based on in-depth knowledge of all damage mechanisms and backed up by appropriate controls. The proposed model (in its various versions) is aimed at supporting the auditing activity and promoting an ageing management based on *knowledge*, *information* and *data*.

Acknowledgments

This work is part of an Italian research entitled "Sviluppo di una Smart Platform (SmartBench) per la sicurezza integrata degli stabilimenti industriali ad Alta Affidabilità" that is supported by INAIL (Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro) within the call BRIC 2016.

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