Knowledge base system (KBS) applied on corrosion damage assessment on metallic structure pipes

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Abstract

This paper aims to outline a proposed knowledge base system (KBS) for the assessment of corrosive damage on metallic pipe conduits. KBS is developed by using two information sources available for assessing the corrosive damage of pipes which are mainly: expert knowledge and field data. In our knowledge, it’s a new method that assists the engineer in his task for assessing the degree of damage on metallic pipes, yielding therefore to a rational evaluation of the corrosive damage (hence the ECOR system) on metallic structures of pipeline, and permits to assign the damage degree on the structure qualitatively while using a ladder of indications representing the severity of each damage type (pitting, crater, weight loss and crack), regarding the priority of either repairing or replacing the metal piece. Furthermore, the analytic hierarchy process is implemented overall the system to determine whether the damage severity requires the engineer intervention in a systematic and rational way.

Keywords: Chemical engineering, Computer science, Materials science

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1. Introduction

Among several parameters causing enormous loss in the field of petroleum industry is the pipes corrosion. Hence, the consequences resulting from this drawback goes beyond loss in production, the cost of replacement, flammability and toxicity of transported products, which often at high pressure could therefore in the major cases influencing serious repercussions, particularly on people security and environment [1]. From this point of view, an inspection program and corrosion monitoring should be taken as an imperative necessity. However, once the cause of the degradation is well known and the severity of the damage is assessed during the inspection, the damaged part must be replaced, making repairs necessary in general. It should be noted, that the assessment and relevance of such an intervention on a system is not an easy task, where a damaged structure does not necessarily require repairs or maintenance. As its well-known, each degradation process occurs in different ways on steels, where its consequences on the functionality, security and integrity of hydrocarbon production plants depend in particular on its evolution over time, other deteriorations and conditions the structure is subject [2]. Thus, optimisation of interventions according to their immediate urgency requires deep analyses which remain therefore complex, even for experimented engineers. In view of the preceding, we developed an innovative methodology based on a new approach, which classifies corrosion damage systems in a rational and homogeneous manner in order to orientate the engineer and facilitates their task towards the required objective for an effective and adequate decision. Indeed, ECOR system has been developed through Expert System [3], also called Knowledge Based System (KBS) to evaluate specifically the damage caused by corrosion on pipeline of plants’ hydrocarbon production with an objective base and platform guidelines. The system includes the knowledge acquired through the literature which englobes methods of damage assessment and expert’s reports [4]. ECOR is therefore an information technology (IT) tool, with a decision support having for goal, the assessment of corrosive’s damage protection and reparation of pipeline, It also serves to optimize the process required for the user by providing orderly data, up-to-date information and capitalizes on the technical knowledge of corrosive degradation of metallic materials [5]. Therefore, this software helps to identify potential causes of corrosive damage in pipeline structures, strictly following the protection system recommendations and the appropriate repair procedures. To achieve this task, the system uses then an integrated and systematic approach in two successive steps involving, a diagnostic module related to the damage assessment, and the other one for repairing.
2. Materials and methods

2.1. The ECOR system approach

This paper aims to highlight and raised the problem through an assessment damage caused by corrosion on a metallic pipeline structure. We demonstrated also during this study, why it is necessary to develop an IT approach, which seems rapid, reliable, rational and capable of responding therefore with efficiency, by introducing an expert system and the validation of human knowledge in metallic corrosion domain [3]. However, the KBS allows the representation of data which have been deduced from guidelines production and an oriented object representation (objects, attributes values with variables) by a simple use of accumulated data. The developed system is presented in three forms as it is indicated in the organigram (Fig. 1), and initiated by a preliminary phase consisting mainly of received information with regards to client file at the disposition of the user (which contains name of organisation

Fig. 1. General flow chart of our expert system.
requiring for expertise, name of person met, function, address, telephone, fax…etc.). It contains also the identification of the metallic plant with a summary description of the structure, while the first set of guidelines is then activated as a result of this given information. In first, module (1) concerns the accumulation of relative data to damage type developed by the metallic structure [6], at this stage, the user introduces the visual observations and other data from damage across the entire interface. Module (2) is related to the assessment of damage using the second set of guidelines saddled to the damage on the structure. The last step is achieved by module (3), which conveys the necessary recommendations in terms of repairs and the fight against corrosion relatively to the damage degree on metallic structure, where it is therefore verified by a third set of guideline [7].

2.2. ECOR consultation

Indeed, the ECOR system begins by displaying a welcome page showing the system’s logo, otherwise, an access to different functions and features of the system through a series of selection button is therefore posted (Fig. 1). During this preliminary phase, more details provided by the user through the interface; specifically the client file and user identification are stopped to prevent the system from using it for reaching conclusions.

2.2.1. Module one (1) description

Module one (1) concerns the identification of types damage on the structure. At this step, we introduce visual observations or other data received through different methods of damage inspection such as, different corrosion types or cracking ones. Hence a detailed observation of each damage type like the maximal expansion of pit, pit number or crater per surface unit, pit or crater localization, where all this data are provided by the user across an interface, yielding therefore an access to damage evaluation which will be achieved by the next module (module 2) [8].

2.2.2. Module two (2) description

The goal of this module is to recognize the severity of damage through an index damage formula within the pipeline element structure. This formula is developed and based on visual observations and weight measurements, which have been entered by the user in module (1).

As it’s indicated in the organigram (Fig. 2), the assessment of severity damage rate on the metallic structure of an element passes through different types of damage and rate severity evaluations such as pits, craters, cracking, piercing…etc. The severity assessment of each damage type for a corrosion pit involves an evaluation of some parameters linked to the pitting such as, the pit diameter and pit density (number of
pits per unit surface). For instance, the assessment of pit density is based on an index: $I_{PD}$ (Pit density Index) which varies from 0 to 5 depending on the pit density, where each pit density value index is related to severity as it’s described in perspective literature (negligible, very reliable, moderate, severe and very severe) [9]. At this level, classifications of different damage parameters permit therefore to relate the degree of severity index to visual observations. However, the drawback is how to combine these two aspects to reach the damage pitting degree, taking into account the influence of pit diameter and its density?, thereby, the analytic hierarchization practice AHP (Fig. 3), seems a useful tool achieving this problematic, and it’s has been used to reach this purpose [10].

2.2.3. Module three (3) description

This module serves to detect, predict and diagnose by means of settled recommendation guidelines of emergency measures, repairing or replacing process for
deteriorated pipes. Yet, as it is has been detailed on Fig. 1, this module is rounded and based on hypothesis issued from module 1 and 2. Based on this, if the level of assessed severity in module 2 is “severe” or “very severe”, therefore the module suggests an emergency measures for reparation or replacement of the element, while these suggestions are therefore the results from selective guidelines. Hence, following these steps, the whole problem data (visual observations) and all conclusions generated by the system are stored therefore in a file, and released every time when needed in the form of a report. The suggested approach will be developed in the Kappa-pc expert system [11]. Generally, the adopted method permits to consider the damage assessment problem as a general default, and considering the simultaneous contribution of different types of corrosion damage and their mutual influence on the total deterioration of the pipe’s element, while the damage types and their factors are structured in the shape of an arborescence, which signifies the sections and sub-sections involving attributed values in Kappa-pc.

2.3. Damage evaluation approach

After determining the shapes, sizes and types of the element’s rupture, the severity of damage is subsequently assessed using the following hypotheses:

1- Complete damage depends on the type of evaluated element.

2- The damage depends on its severity and condition of ruptures (pitting, cracking...etc.) with each type of rupture having certain influence on the total damage of an element [12].
3- The damage severity of each rupture sign depends on the shown severity, and different appearance factors are considered.

4- A scale of six severity levels is used in order to classify damages through introduction index [9].

5- A literal descriptor is assigned to each severity level or index.

6- The service condition, the security condition, aesthetic and repairing costs are all criteria upon which damage assessment is made.

It’s should be noted; during this research, only the first item was undertaken, where the damage evaluation has been mainly based on visual observations of the pipelines, while this analytic hierarchization method (AHP) allows to exploit this information in a logical and rational way [13].

The AHP is a method mainly considering the elements of problem as a body, and split up into a sub problem by using series of conclusive decisions to develop a hierarchic analytical operation, while its execution leads to a final matrix representing the general alternative priorities linked each one to the other. Hence, a logical decision based on the comparison of the results between the criteria and alternatives is therefore taken into consideration. In addition, this method serves also to establish simple comparisons among the developed factors during making decision [9]. Otherwise, in brief a multiple aspect method assisting to make decision, tolerating a slight uncertain and acceptable in terms of data and judgment. In another aspect, it is an analytic method involving numbers so as to describe the decision, whereas the hierarchization involves the structuration of the making decision corresponding to well-known the problem.

### 2.3.1. Analytic hierarchization implementation method

As shown in (Fig. 3), the damage assessment method can be represented as a succession of hierarchies, where the highest level or hierarchy’s peak is the damage assessment on the main pipe element as primary objective. The next level is made up with several parameters such as: service and security condition, aesthetics, repairing cost...etc. Thus, these parameters correspond to the criteria on which the next level is indeed evaluated, in our case; the signs of damage include extensive pits, surface condition, fissures, weight loss and others. The last level displays a set of damage factors (fissure width, depth and density) which affect the deterioration signs.

However, identifying factors is the most determinative step, where their classification is therefore achieved by predominant and secondary ones, through hierarchy and/or by setting priorities for such elements at each level. In first, establishing element’s priorities is to make comparisons, in such process requires elements (I, j) comparison in pair according to the given criterion, and the matrix form is most suitable way for this task. Thus, to fill the matrix, a scale of numbers from 1 to 9 is used.
in order to represent the relative element by importance one to the other and at the same time, considering some feature due to the deterioration. According to the AHP method, the values from 1 to 9 are detailed as follows [10]:

1- The importance element intensity (represented by I) is the same as the “j” element, in other words, “I” and “j” are important as well.

3- Means that the intensity importance of the element “I” compared to “j” is slight or moderate i.e. the experience or judgement suggests a slight preference to one over another.

4- Signifies the intensity importance of the element “I” compared to “j” is fundamentally essential or high, i.e. the experience or judgement suggests a high preference to one over another.

7- Shows that the significance of element “I” intensity compared to “j” is highly advanced or demonstrated by experience.

9- Means that the damage is absolute. Therefore, the evidence of “I” prevailing over “j” is an absolute statement.

Where 2, 4, 6 and 8 correspond to an intermediate importance degree of levels which are previously defined and which thus promote further arbitration. Reciprocally, if the element “j” is compared to “I”, the assigned values are reversed, for instance if the degree of importance in the case of the first element (i = 1) in a hierarchy compared to the second (j = 2) is equal to 3, meaning that the second importance element intensity compared to the first is 1/3. The Fig. 3 illustrates the analytic hierarchization method in damage assessment due by cracking.

3. Results and discussion

3.1. Index damage calculation

The damage evaluation in this research is majorly based on the overall damage rate directly related to visual observation of metallic element condition and weight loss measurements. However, in order to assess the damage caused by corrosion, an indexed system is thus suggested by evaluating the danger degree through calculation of the total index corrosion damage from partial index [14]:

- Pitting severity index $I_p$
- Crack severity index $I_F$
- Craters severity index $I_{Cr}$
- Weight loss severity index $I_{Unif}$

Otherwise, the damage severity is evaluated from the following hypotheses:
1- The overall damage depends on the severity of each corrosive degradation condition (pitting, crack, crater and weight loss)

2- The damage severity of each degradation sign depends on the appearance severity of the degradation sign.

3- A scale of five severity levels is implemented in order to classify the damage by means of index [9].

4- Each severity level corresponds to literal descriptor (very severe, severe, moderate, low, very low or none). However, the total index has been conceived to guide the engineer for the right decision, relative choice and periods of reparation made on the pipeline element. This parameter leads the engineer’s decision horizontally and vertically through the hierarchy (Fig. 3). This evaluation method stands for a hierarchic series, and the highest level or peak is therefore the main objective. The next phase is made up with several constituents (service condition, security condition, aesthetics, repairing cost….etc), corresponding to the criteria on which the following level in the hierarchy will be assessed i.e. in this case, the damage signs (pitting corrosion, surface condition, cracking, etc.). The last level (or the lowest one) displays a damage factor set (pit diameter, pit density, extent, etc.) having an impact on damage signs [15].

3.1.1. Damage assessment index by pitting corrosion

The most factors which must be taken into consideration while assessing the pitting severity for a corroded pipeline are the aperture diameter of the pit or its density. Once identified, these factors are classified according to their influence or relative priority on the severity. Table 1 shows a comparison matrix (in pairs) of every factor compared to the impact of each on the pit. If a factor is compared to itself the result is then 1, thus the matrix diagonal line is composed of 1, which means the same thing goes for all diagonal matrix comparing pairs of equal type. When a factor is compared to another, experts’ judgments in the concerned field of evaluation is sought, which means, assigning prioritized factors to interpret relative importance of pitting factor in regards to the other one [16].

| Matrix diameter of the observed pitting (mm) | Priority factor | Pit depth $p_{dep}$ | Pit diameter $p_{dp}$ | Pit density $p_{Dp}$ |
|---------------------------------------------|---------------|-------------------|------------------|-------------------|
| Pit depth                                  | 1             |                   |                  |                   |
| Pit diameter                               |               | 1                 |                  |                   |
| Pit density                                |               |                   | 1                 |                   |

Table 1. Comparison matrix (in pairs) of each priority factor by their influence on each other on the pitting.
In order to simplify the only considered factors are “pit depth” and “pit diameter” [16], every factor is expressed in the form of an index linked with its severity, and combined to bring about the pit index and determined according to the following equation:

\[ I_P = P_{dp} \cdot I_{dp} + P_{Dp} \cdot I_{Dp} \]  

(1)

\( I_P \): Pitting damage index.  
\( I_{dp} \): Pit diameter damage index  
\( I_{Dp} \): Pit depth damage index  
\( P_i \): weighing factor for each damage sign which is defined by:

\[ P_i = \sum p_i \]  

(2)

Where \( p_i \): priority or importance factor assessed by experts through the analytic hierarchy method [13].

The weighing factor reflects the importance degree of each pitting. To determine the priority factors of pits (pitting factor) \( p_i \), the following hypotheses are hence established:

Tables 2 and 3 illustrate different extensive pit depth and diameter with a corresponding severity rate. During the structure element assessing the maximum extensive pit depth compared to the thickness of the pipe should be noted and compared therefore to the values in the Table 2.

The Table 3 shows the the maximum extensive pit diameter interval observed at the element surface, as well as their rates and severity description associated, more the pit diameter increases, its severity rises, as the corrosive potential [15].

To determine the extensive-pit importance factors, the following hypotheses are elaborated:

**Table 2. Pitting depth index and severity damage.**

| Index \( I_{Dp} \) | Depth pits compared to pipe thickness (%) | Severity |
|--------------------|----------------------------------------|----------|
| 0                  | No pit                                 | None     |
| 2                  | 0% < depth ≤ 20%                       | Low      |
| 3                  | 20% < depth ≤ 30%                      | moderate |
| 4                  | 30% < depth ≤ 50%                      | Severe   |
| 5                  | 50% < depth ≤ 70%                      | Very severe |
When the pit depth is assessed as “very severe”, its impact on total damage due to extensive pits is maximum or absolute, without taking in consideration the pit diameter.

In the case where pit depth is assessed as “low”, the pit diameter severity prevails.

In the remaining cases, the AHP method is therefore applied.

The importance factors $P_i$ are independent on the considered element structure.

On the Table 4, values are estimated by considering the relative contribution of extensive pit depth and its diameter. Hence, this estimation has been made by experts in the concerned research field with corroded structure elements.

Thus, according to the relative importance scale of Saaty [10], the pit depth impact is four times more important than the diameter one in the deteriorated element and reciprocally, meaning the pit diameter impact corresponds to a quarter of the pit depth impact. The Table 5 shows the final weighing and importance factors with the previous mentioned hypotheses.

However, these factors and respective $P_i$ depth (or pit diameter) index values are injected in Eq. (1) to evaluate the failure rate value. The Table 6 summarise the different severity index corresponding to corrosion by extended pits.

### 3.1.2. Damage assessment index by crater corrosion

In the case of degradation caused by crater corrosion, the mainly required factor is the damage extension as it’s represented in Table 7 [17].

| Index $I_{dp}$ | Maximum extensive pit diameter (mm) | Severity |
|---------------|-------------------------------------|----------|
| 0             | No pit                              | None     |
| 1             | $0 < D \leq 1$                      | Low      |
| 2.5           | $1 < D \leq 2$                      | Moderate |
| 4             | $2 < D \leq 3$                      | Severe   |
| 5             | $3 < D \leq 5$                      | Very severe |

| Pitting damage impact | Priority factor |
|-----------------------|-----------------|
| Pit depth $p_{dp}$    | Pit diameter $p_{dp}$ |
| Pit depth             | 1               | 4               |
| Pit diameter          | 1/4             | 1               |

Table 3. Pitting diameter index and severity damage.

Table 4. Priority factor between extensive pit diameter and density.
3.1.3. Damage assessment index by weight loss

In particular, the assessment involves a parameter which measures thickness loss compared to the admissible weight determined by service condition. The Table 8 describes briefly the observed weight loss index with an associated rating. Otherwise, the weight severity loss increases and it’s should not reaching a minimum severe weight threshold, which is determined according to maximum severe pressure as it is stated in expression (3) [18, 19].

\[
E = \left( \frac{P_{\text{max}} \cdot D}{R \cdot C} \right) \times 100
\]  

\(E\): threshold minimal thickness  
\(P_{\text{max}}\): maximum pressure of service (kgcm\(^3\))

Table 5. Weighing and priority factor.

| Case | Weighing factor | Priority factor |
|------|-----------------|-----------------|
|      | \(P_{Dp}\)     | \(P_{dp}\)     | \(P_{Dp}\) | \(P_{dp}\) |
| 1    | 1               | 0               | 1           | 0           |
| 2    | 0               | 1               | 0           | 1           |
| 3    | 4/5             | 1/5             | 4           | 1           |

Case 1: damage assessment of pit depth very severe.  
Case 2: damage assessment of pit depth: low.  
Case 3: damage assessment of pit depth moderate or severe.

Table 6. Pitting index and severity damage.

| Pitting index \(I_p\) | Severity     |
|-----------------------|--------------|
| 0                     | None         |
| \(0 < I_p \leq 3.5\)  | Moderate     |
| \(3.5 < I_p \leq 4.5\) | Severe       |
| \(4.5 < I_p\)         | Very severe  |

3.1.3. Damage assessment index by weight loss

In particular, the assessment involves a parameter which measures thickness loss compared to the admissible weight determined by service condition. The Table 8 describes briefly the observed weight loss index with an associated rating. Otherwise, the weight severity loss increases and it’s should not reaching a minimum severe weight threshold, which is determined according to maximum severe pressure as it is stated in expression (3) [18, 19].

\[
E = \left( \frac{P_{\text{max}} \cdot D}{R \cdot C} \right) \times 100
\]  

\(E\): threshold minimal thickness  
\(P_{\text{max}}\): maximum pressure of service (kgcm\(^3\))

Table 7. Damage Index and severity, crater extent.

| Index \(I_{Cr}\) | Crater extent per dm\(^2\) (%) | Severity |
|------------------|-------------------------------|----------|
| 0                | No crater                      | None     |
| 3                | 0% < extent \(\leq 10\)%      | Moderate |
| 4                | 10% < extent \(\leq 35\)%     | severe   |
| 5                | 35% < extent \(\leq 50\)%     | Very severe |
3.1.4. Damage assessment index by cracking corrosion

The main origin of this type of corrosion is due to the mechanical properties, and resulting from temperature pressure, vibration... etc. Two types of crack have been elaborated in regard of the ending shape of the structure [20].

1. Crack propagation: the top is a peak.
2. Low crack: the top is a peak, flat or rounded.

In these cases, the procedure of cracking index determination is similar to pitting ones. When a structure element is split, several factors have to be considered during the cracking severity assessment such as the width and/or the extent of the shape extremity. However, once these parameters have been identified, they will be therefore sorted out according to their impact or their relative priority over the cracking severity. The Table 9 displays a comparison matrix by every priority factor $p_i$ compared to its impact on the cracking process. If a factor is compared to itself, the result is one, meaning the diagonal line is therefore made up of 1, whereas the experts’ judgment occurs for factors compared to the others, while it is imperative to assign priority factors reflecting the relative importance of one cracking factor to the other [13].

| Maximum width of crack Observed (mm) | Priority factor |
|--------------------------------------|-----------------|
|                                      | $p_{lf}$ | $p_{df}$ | $p_{ext}$ |
| Crack width                          | 1        |          |           |
| Crack density                        |          | 1        |           |
| Shape extremity of Crack             |          |          | 1         |
The cracking severity index is undertaken in the same way of extensive pits, and every factor is therefore expressed in terms of the cracking width index involving the density and the extremity shape one, where these factors are weighed afterwards to deduce a final crack index (Eq. 4).

\[ I_F = P_{ILf} \cdot I_{ILf} + P_{Ifext} \cdot I_{Ifext} + P_{IDf} \cdot I_{IDf} \]  

(4)

With:

- \( I_F \): Crack damage Index
- \( I_{ILf} \): Damage index crack width
- \( I_{IDf} \): Damage index crack density
- \( I_{Ifext} \): Damage index crack extremity shape
- \( P_i \): Weighing factor for every damage sign defined by Eq. (2)

The Table 10 illustrates different crack widths with the corresponding severity index. Otherwise, during the structure element estimation, the maximum cracking width value observed at the element surface should be noted and compared to the value elaborated in the Table 10.

More crack width increases more the severity damage rises, because of the corrosion risk under tension, which is a synergic phenomenon between mechanical and electro-chemical phenomena [21]. The Table 11 shows the crack density intervals possibly observed at the element surface with the severity associated description rate.

The Table 12 shows the intervals of the shape extremity of possible cracks observed at the element surface with their associated severity rates description.

In order to determine the importance factors of cracking (\( p_i \)) the following hypotheses are established:

1. When the crack width is assessed as “very severe”, its impact on the overall deterioration by crack is maximum or absolute, without any consideration to cracking density.
2. The cracking density severity prevails in the case where the crack width has been evaluated as “low”

| Table 10. Damage severity and index by crack width severity. |
|-------------------------------------------------------------|
| Index \( I_{ILf} \) | Crack width | Severity |
|----------------------|--------------|-----------|
| 0                    | 0            | None      |
| 1 – 2                | 0.5 < \( L_F \) < 1 | Severe    |
| 3 – 5                | \( L_F > 1 \) | Very severe |
3. For the remaining cases, the AHD method is applied.
4. Importance factors $p_i$ are independent on the considered structure element.

In the Table 13, the values are assessed while considering the relative contribution of the crack width and density to cracking deterioration. Such estimation is mainly based in particular on experts' judgment within the field.

According to the relative importance Saaty scale [10], it has been assessed that the cracking width impact is four times more important than the cracking density on corroded element and reciprocally, the impact of crack density corresponds to a quarter of the impact of the crack width, as well as to a quarter of the impact of the crack extremity [22]. The Table 14 shows the final weighing and priority factors as they were mentioned previously.

These factors and the respective rate values of crack width density take place in Eq. (4), in order to determine the cracking rate value.

Table 15 sums up the different severities and rates corresponding to the corrosion by cracking.

### Table 11. Crack density index and severity damage.

| Index $I_{cr}$ | Cracking density (%) | Severity |
|----------------|-----------------------|----------|
| 0              | 0                     | None     |
| 1-2            | 0 < $D_F$ < 3%         | Severe   |
| 3-5            | 3% < $D_F$            | Very severe |

### Table 12. Shape extremity index and severity damage.

| Index $I_{ext}$ | Shape extremity | Severity |
|-----------------|-----------------|----------|
| 0               | No cracking     | None     |
| 1-2             | Rounded, flat   | Severe   |
| 3-5             | peak            | Very severe |

### Table 13. Priority factor between cracking width and density.

| Damage influence | Priority factor |
|------------------|-----------------|
|                  | Cracking width $p_{LF}$ | Cracking density $p_{DF}$ | Cracking shape $p_{ext}$ |
| Cracking width    | 1               | 4                       | 4                       |
| Cracking density  | 1/4             | 1                       | 4                       |
| Shape extremity   | 1/4             | 1/4                     | 1                       |
3.1.5. Total damage index assessment

Determining the total damage index is undertaken by considering the pitting index, then the crater corrosion along with thickness loss and cracking [23]. The total weighed index of corroded pipe element is calculated by the following equation:

\[ I_{Tot} = P_P \cdot I_P + P_{Cr} \cdot I_{Cr} + P_{Unif} \cdot I_{Unif} + P_F \cdot I_F \]  

\( I_{Tot} \): Total damage index  
\( I_P \): Pitting damage index  
\( I_{Cr} \): Crater damage index  
\( I_{Unif} \): Loss of thickness damage index  
\( I_F \): Cracking damage index  
\( P_i \): Weighing factor of every damage sign as defined in Eq. (2)

During the global assessment, the relative importance of extensive pits, craters, weight loss and cracking have been considered in the priority matrix (Table 16).

These suggested pitting priority factors stand for every damage contribution type to the global corrosion process, with regards to the security criterion. The first priority matrix column describes the crater impact, the weight loss and cracking, Table 14. The final weighing and importance factors with the previously mentioned hypotheses.

| Case | Weighing factor | Priority factor |
|------|----------------|----------------|
|      | \( P_{Lf} \)   | \( P_{Df} \)   | \( p_{Lf} \) | \( p_{Df} \) |
| 1    | 1              | 0              | 1             | 0             |
| 2    | 0              | 1              | 0             | 1             |
| 3    | \( 4/5 \)      | \( 1/5 \)      | 4             | 1             |

Case 1: damage assessment to crack width is “very severe”.  
Case 2: damage assessment to crack width is “low”.  
Case 3: damage assessment to crack width is “moderate” or “severe”.  
\( P_{Lf} \): Weighing factor for crack width.  
\( P_{Df} \): Weighing factor for crack density.  
\( p_{Lf} \): Priority factor for crack width.  
\( p_{Df} \): Priority factor for crack density.

Table 15. Crack index and severity damage.

| Cracking index \( I_F \) | Severity |
|--------------------------|----------|
| 0                        | None     |
| 0 < \( I_F \) < 3.5      | Severe   |
| 3.5 < \( I_F \)         | Very severe |

3.1.5. Total damage index assessment

Determining the total damage index is undertaken by considering the pitting index, then the crater corrosion along with thickness loss and cracking [23]. The total weighed index of corroded pipe element is calculated by the following equation:

\[ I_{Tot} = P_P \cdot I_P + P_{Cr} \cdot I_{Cr} + P_{Unif} \cdot I_{Unif} + P_F \cdot I_F \]  

\( I_{Tot} \): Total damage index  
\( I_P \): Pitting damage index  
\( I_{Cr} \): Crater damage index  
\( I_{Unif} \): Loss of thickness damage index  
\( I_F \): Cracking damage index  
\( P_i \): Weighing factor of every damage sign as defined in Eq. (2)
compared to damage due to extensive pits. The corrosion pits induce the same impact as the extensive pits over the global damage on structure element. The weight loss involves a slightly inferior contribution to extensive pits corrosion. The impact due to cracking is sharply superior to the extensive pits over the global damage on the corroded structure [24, 25].

### 3.1.5.1. Observations

If one or more degradation conditions are not developed, it will obviously not contribute to the total damage, and then the value 0 is assigned to the priority factors. The following Table englobe the priority factors for every standardized degradation condition, compared to pit corrosion, or in the case where no damage had been observed. The Table 17 assigns to each index a corresponding severity, while the attribution of values allows in consideration the relative gravity of each degradation, meaning the higher deductible value induce therefore a rise in damage severity.

In the present study, the total damage index determination passes initially through the calculation (Eq. (5)) of deductible weighed values in the observed deterioration. However, the damage assessment method presented above remains a tangible approach, which is elaborated by some experts weighing by indexes (Eq. (5)) and responding to the knowledge of the exact relative importance of each indicator. To improve this calculation method, the coefficients and index values must be adjusted again. Hence, it should be noted, the discussed calculation in this paper

| Security limit | Priority factor | Pit $p_F$ | Craters $p_{Cr}$ | Thickness loss $p_{Unif}$ | Cracking $p_F$ |
|----------------|----------------|----------|------------------|----------------------|----------------|
| Pits           | 1              | 1        | 2                | 1/2                  |
| Craters        | 1              | 1        | 1/2              | 1/3                  |
| Thickness loss | 1/2            | 2        | 1                | 1/3                  |
| Cracking       | 2              | 3        | 3                | 1                    |

Table 16. Priority factor for different damage types observed on a structure element.

| Total damage Index $I_{Tot}$ | Severity       |
|-----------------------------|----------------|
| 0                           | None           |
| $0 < I_{Tot} \leq 1$         | Moderate       |
| $1 < I_{Tot} \leq 2.5$       | Severe         |
| $2.5 < I_{Tot}$              | Very severe    |

Table 17. Total Damage index calculated according to Eq. (5) and the associated severity.
is not necessarily optimal, but is known to be coherent and comprehensive throughout its diverse steps.

As mentioned above, and as an alternative to improve the efficacy and to make a comprehensive overview of the proposed method, the Table 18 summaries a real case of pipe damage assessment.

### 4. Conclusion

The damage index is an indicator factor allowing the quantification of damage through different degradation signs, and by implementing visual inspection data collected previously on a pipeline element. The developed ones within the presented system aim to exclude the engineer’s subjectivity to determine path of pipelines requiring prioritized intervention during the assessment operation. Therefore, this is made possible by intensifying the evaluation of every phenomenon with exhaustive classification. However, the given factors such as, extensive pit index ($I_p$), corrosion crater index ($I_{Cr}$), weight loss ($I_{Unif}$), or cracking index ($I_f$), it becomes feasible to objectively confront the whole damage parameters of the pipeline. Indeed, the methodology developed herein is mainly based on a calculation approach by using rational varied parameters in order to classify them in homogenous way. However, the model’s sensitivity being verified and requires the use of the damage index which is executed with necessary precautions. In the same context, the diverse parameters presented should probably adjusted in order to better enhance and refine the system, while the damage index seems to be a useful tool and mainly serves to guide not impose or fix decisions of the engineer in charge of inspections. Finally, in our

| Identification of damage | Pitting corrosion | Crater | Weight loss | Cracking |
|--------------------------|------------------|--------|-------------|----------|
| Index & severity         | Depth            | Diameter | extent per dm² (%) | Rate | width  | Density | Shape extremity |
| 50% severe               | 2 mm             | moderate | 0 | 20% | moderate | 0.8 mm | severe | 1% severe | peak very severe |
| Priority factor          | 4                | 1       | 0 | 1 | 4 | 1 | 1 |
| Weighting factor         | 4/5              | 1/5     | 0 | 1 | 4/6 | 1/6 | 1/6 |
| Index                    | 4                | 2.5     | 0 | 2 | 2 | 1 | 3 |
| Priority factor          | 2                | 0       | 1 | 3 |
| Weighting factor         | 2/6              | 0       | 1/6 | 3/6 |
| Total index              | $2/6 \times 3.5 + 0 \times 0 + 1/6 \times 2 + 3/6 \times 2 = 2.5$ | |
| Total severity           | severe           | |

Table 18. Case study scenario:- Damage assessment.
knowledge, it could be tempting to adopt the verdict that proceeds from an advanced technology system but keep in mind that no tool or methodology of this nature can outdo the final judgment of human arguments.

**Declarations**

**Author contribution statement**

Nabil Cheriet: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Nacer-Eddine Bacha: Performed the experiments; Analyzed and interpreted the data.

Abdelhak Skender: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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**Competing interest statement**

The authors declare no conflict of interest.

**Additional information**

No additional information is available for this paper.

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**References**

[1] A. Benmoussa, External damage by corrosion on steel gas pipeline, Eurasian ChemTech J. 3 (2001) 285–289.

[2] J.F. Kiefner, W.A. Maxey, R.J. Eiber, A study of the causes of failure of defects that have survived a prior hydrostatic test, in: Pipeline Research Committee, American Gas Association, 1980, November. NG-18, Report No. 111 (3).

[3] S. Audisio, Expertise corrosion, database and expert systems, Matériaux Tech. 99 (2011) 65–80.
[4] H. Castaneda, O. Rosas, Oil and gas pipelines, in: R. Winston Revie (Ed.), External Corrosion of Pipelines in Soil, Integrity and Safety Handbook, 2015, pp. 265–274.

[5] Canadian Energy Pipeline Association CEPA, Stress Corrosion Cracking, in: Recommended Practices, second ed., Calgary, 2007, December.

[6] K. Valavanis, A.I. Kokkinaki, S.G. Taffetas, Knowledge-based (expert) systems in engineering applications: a survey, J. Intell. Rob. Syst. 10 (2) (1994) 113–145.

[7] E.J. Carl, O.H. Brian, A.B. William, Pipeline Repair Manual, in: Pipeline Research Council International Catalog. No. L52047, 2006, August. Houston, Texas.

[8] S. Peet, J. Race, J. Dawson, Pipeline Corrosion Management, 11–16, NACE International, Houston, Texa, 2001, March.

[9] Y.S. Park, S.Y. Han, B.C. Suh, E.R. Kim, S.J. Park, A Proposal for Damage index of Steel Members under Severe Seismic Loading, Conf. Earthquake Engineering, Vancouver, B.C., 2004, August.

[10] T.L. Saaty, A scaling method for priorities in hierarchical structures, J. Math. Psychol. 15 (3) (1977) 234–281.

[11] Kappa PC version 2.4, User Manual Intellicorp, IncCA, 2007.

[12] M. Jakubowski, Influence of pitting corrosion on fatigue and corrosion fatigue of ship and offshore structures, part II: load − pit − crack interaction, Pol. Marit. Res. 3 (87) (2015) 57–66.

[13] T.L. Saaty, Decision making with the analytic hierarchy process, Int. J. Serv. 1 (1) (2008) 83–98.

[14] A. Cosham, P. Hopkins, The assessment of corrosion in pipelines — guidance in the pipeline defect assessment manual (PDAM), in: Conf. Pipeline Pigging and Integrity Management, Amsterdam, 17–18th, 2004, May.

[15] G.S. Frankel, Pitting corrosion of metals. A review of the critical factors, J. Electrochem. Soc. 145 (6) (1998) 2186–2198.

[16] F. Pessu, R. Barker, A. Neville, Understanding pitting corrosion behavior of X65 carbon steel in CO2-saturated environments: the temperature effect, Corrosion 72 (1) (2016) 78–94.

[17] S. Timashev, A. Bushinskaya, Methods of assessing integrity of pipeline systems with different types of defects, in: Springer (Ed.), Diagnostics and Reliability of Pipeline Systems, Topics in Safety, Risk, Reliability and Quality, 30, Springer International Publishing, Switzerland, 2016, pp. 9–43.
[18] A.F. Touabti, K. Younsi, A. Smati, Transient analysis helps IM for crater-type corrosion defects, Oil Gas J. 111 (11) (2013) 94–102.

[19] P. Ellenberge, Piping and Pipeline Calculations Manual, in: Construction, Design Fabrication and Examination, Butterworth-Heinemann, 2014.

[20] NACE Standard MR-01-75, Standard Material Requirements — Metals for Sulfide Stress Cracking and Stress Corrosion Cracking Resistance in Sour Oilfield Environments for Sulfide Stress Cracking Resistant Metallic Material for Oilfield Equipment. Sec. 3 and 5, 2003. Houston, Texas.

[21] M.S. Attia, M.M. Megahed, A. Darwish, S. Sundram, Assessment of corrosion damage acceptance criteria in API579-ASME/1 code, Int. J. Mech. Mater. Des. 12 (1) (2014) 1–11.

[22] Y.F. Cheng, Stress Corrosion Cracking of Pipelines, A John Wiley & Sons, Inc., Hoboken, New Jersey, 2013.

[23] K.Y. CHOI, Morphological analysis and classification of types of surface corrosion damage by digital image processing, Corrosion Sci. 47 (1) (2005) 1–15.

[24] A.W. Peabody, Control of Pipeline Corrosion, second ed., NACE International, Houston, TX, 2001.

[25] J.M. Kulicki, Z. Prucz, D.F. Sorgenfre, D.R. Mertz, Guidelines for evaluating corrosion effects in existing steel bridges, in: Reports of the National Cooperative Highway Research Program, 1990, December.