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Matching of corroded defects in onshore pipelines based on In-Line Inspections and Voronoi partitions

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Abstract

Onshore pipelines are usually subjected to a corrosion attack. Regular inspections known as In-Line inspections (ILI) are commonly used with magnetic (MFL) or ultrasonic (UT) tools to prevent any failure. New defects will appear between consecutive inspections due to the aggressiveness of the surroundings and the detection thresholds associated with the defects' depth. This work focuses on the matching problem between two inspections, aiming to identify the degradation increments and the position of new defects. Typically, it is linked to the well-known point matching problem in pattern recognition, where the objective is finding the best affine transformation between two sets of points in a plane. This work presents an alternative using Voronoi cells to filter possible matches and an iterative approach to determine the best affine transformation, considering the uncertainty in any direction. The approach was implemented for a real pipeline 45 km long and for synthetic corrosion defects, allowing us to identify possible matches easily. Based on the *new* and *old* defects, some insights about the probability of detection and false alarm are deduced. For this purpose, experimental probability and results from recognized exponential and log-logistic functions were considered.

Keywords: Corroded pipeline, New defects, matching, Probability of detection, Voronoi cells

1. Introduction

Onshore pipelines are critical components in the chain of production and distribution of oil and gas. These pipelines are generally subjected to extreme operation and environmental conditions that would lead to significant corrosion failure risks [1–4]. Therefore, condition assessment through inspections is crucial to ensure adequate levels of serviceability and safety. Corroded pipelines are commonly inspected with Magnetic (MFL) or ultrasonic (UT) tools following In-Line Inspection (ILI). These inspections provide the location and the extent of the metal loss detected based on the pipeline abscissa (longitudinal direction) and a 12-hour clock analogy for the circumferential position. This information is used to monitor the evolution of the corrosion attack every 2 to 6 years to support future maintenance and repair decisions. The challenge lies in the fact that these measurements are subjected to different uncertainties associated with the existence, position, and magnitude of the corrosion defects; for instance, ILI tools have a detection threshold of the depth of the defects near 10% of the wall thickness. Although ILI tools include this threshold, the detection problem does not follow a binary output where every defect above it would be indeed detected. On the contrary, there is a detection error in terms of the probability of being detected (PoD) and being a false alarm (PFA) [5]. These probabilities are intrinsically correlated with the reported accuracy for the defect depth measurements, where it follows that the depth of the defects reported by ILI (d_{ILI}) is related to the real depth (d_{real}) by $d_{ILI} = d_{real} \pm 0.1t$ at 80% certainty.

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Other uncertainties include shifted positions and the appearance of new defects possibly caused by a noise signal, complicating any direct matching between consecutive inspections to monitor the pipeline’s condition. These new defects can be associated, on the one hand, with the aggressiveness of the surrounding soil, fluid operation, and fluid properties [6]. Several authors agreed that corrosion is favored when the resistivity is reduced regarding soil aggressiveness. Besides, it can be affected by the soil porosity, and groundwater conductivity [7]. Whereas the flow velocity, Zhang and co-workers have obtained that a low flow velocity (< 2 m/s) may lead to a competition between the corrosive species and the inhibitor, and at high velocities (> 6 m/s), an erosion-corrosion may be favored [8]. On the other hand, the new corrosion defects can appear due to a miss-detection in the first inspection or a false alarm in the second one. The reason why new defects appear is unknown without field measurements, but there is certainly an “indication” of a new corrosion point based on the reported in the ILI measurement.

Matching these corrosion defects is associated with the well-known point-matching problem for pattern recognition. This problem seeks an affine transformation using translation, scaling, and rotation parameters to match the highest number of pairs between the two inspection results. There are some available alternatives in this regard for pattern recognition, such as the Iterative Closest Point (ICP) of Besl & McKay [9] or the Thin Plate Spline Robust Matching (TPS-RPM) of Chui & Rangarajan [10]. For corroded pipelines, Dann & Dann [11] proposed a modified version of the TPS-RPM approach, considering possible displacements of the corrosion between inspections based on an Annealing algorithm. This approach seeks an affine transformation matrix with defined rotation, translation, and scaling factors. Considering the uncertainty in the results of the inspection, regarding the longitudinal and circumferential location of corrosion defects, it might be possible that the final matching may not be completely described by this transformation. This work presents an alternative framework to identify which points are classified as *new* and *old* defects using Voronoi partitions to filter preliminary matches and an iterative matching transformation. This framework is applied to a real pipeline of 45 km and synthetic corrosion defects. The approach incorporates location uncertainties and correspondence analysis with outlier filtering. The results in the real and synthetic measurements highlight this framework to be considered by pipeline operators in further condition-based monitoring. The result also allows us to discuss some insights into how this probability can be estimated using the depths of the *new* defects.

The document is structured as follows: Section 2 describes the point-matching problem and the main matching alternatives for pattern recognition. Section 3 introduces the matching alternative for the corroded pipeline and some drawbacks. Section 4 presents the proposed matching approach using a Voronoi partition. Section 5 characterizes the spatial dependencies of the real case study. Section 6 discusses the matching results for the real and synthetic measurements. Section 7 presents some insights about the probability of detection and false alarm, and Section 8 gives the final conclusions.

2. Point matching problem: Identifying new defects between inspections

2.1. General problem formulation

The point matching problem considers two sets of points $\mathcal{P} = \{p_i \in \mathcal{W}, i = 1, 2, \dots, n\}$ and $\mathcal{Q} = \{q_k \in \mathcal{W}, k = 1, 2, \dots, m\}$, which represent the defects from the first and second ILI measurement, respectively. In this case, p_i and q_k are vectors containing the location of the pipe and $\mathcal{W} = (\mathbb{A} \times \mathbb{P}) \subset \mathbb{R}^2$ is the plane produced by the abscissa and clock-position once the pipeline is unrolled axially. The traditional point pattern problem search for an affine transformation T for $p_i := (x_{p_i}, y_{p_i})$ given by:

$$T \begin{pmatrix} x_{p_i} \\ y_{p_i} \end{pmatrix} = \begin{pmatrix} t_x \\ t_y \end{pmatrix} + S \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x_{p_i} \\ y_{p_i} \end{pmatrix}, \quad (1)$$

where S is a scaling factor, θ is a rotating angle and t_x and t_y are translations in both main directions. Figure 1 illustrates this matching problem. According to Van Wamelen et al. [12], a matching between the two sets of observations would take place, given a matching probability $\delta \in [0, 1]$ and a matching size $\gamma \in \mathbb{R}$, if there exists a subset of δn points \mathcal{P}_M of \mathcal{P} such that for each $p \in \mathcal{P}_M$ it follows that $\|T(p) - q\| < \gamma$ for a $q \in \mathcal{Q}$.

2.2. Matching alternatives

Point pattern matching is a problem that has been studied before in the field of pattern recognition through different approaches, including fuzzy relaxation, asymmetric neural networks, 2D clustering, and nearest neighbor search

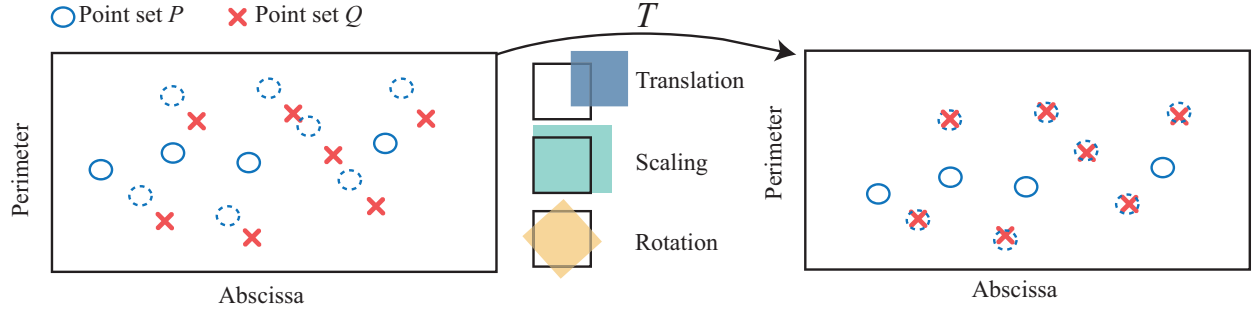


Figure 1: Scheme of the point matching problem.

approaches [12]. Most of these approaches implement a filter approach to determine the number of $\ell \leq \min(n, m)$ of possible matches. One alternative is the Iterative Closest Point (ICP) algorithm that uses the set of nearest neighbors of the points in \mathcal{P} from the points \mathcal{Q} , here denoted as $\mathcal{O} := \{o_1, \dots, o_n\}$, in a quaternion-based algorithm that implements an optimal translation \bar{q}_T and rotation $\bar{q}_R = [q_0, q_1, q_2, q_3]^t$ transformations [9]. The latter is associated with a unit quaternion (i.e., $q_0^2 + q_1^2 + q_2^2 + q_3^2 = 1$). The objective is to minimize the following function:

$$f(\bar{q}) = \frac{1}{n} \sum_{i=1}^n \|o_i - R(\bar{q}_R)p_i - \bar{q}_T\|^2$$

where $\bar{q} = [\bar{q}_R \bar{q}_T]$ and R is the rotation matrix that is produced by the unit quaternion rotation as follows:

$$R = \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2(q_1q_2 - q_0q_3) & 2(q_1q_3 + q_0q_2) \\ 2(q_1q_2 + q_0q_3) & q_0^2 + q_2^2 - q_1^2 - q_3^2 & 2(q_2q_3 - q_0q_1) \\ 2(q_1q_3 - q_0q_2) & 2(q_2q_3 + q_0q_1) & q_0^2 + q_3^2 - q_1^2 - q_2^2 \end{bmatrix}.$$

65 Following the closed-solution reported by Horn [13], the optimal rotation transformation \bar{q}_R is determined from the
 66 eigenvector of the maximum eigenvalue of the symmetrical matrix whose elements are combinations of sums of
 67 products of the point coordinates. Optimal translation \bar{q}_T corresponds with the difference of the centroid of points in
 68 \mathcal{Q} (center of mass) and the rotated centroid of points in \mathcal{P} . This process follows iteratively until the difference between
 69 iterations of the mean square error of the point matching converges to a predefined threshold [9], which can be linked
 70 to the accuracy of the location.

Other alternatives consider not only the nearest neighbor, but also the k nearest neighbors of each point in both sets. For instance, the approach reported by Van Wamelen et al. [12] compares the k nearest neighbors of each point p_i with the points in q_k and determines its local affine transformation with the approach reported by Chang et al. [14]. Chang and co-workers proved that if there are ℓ pairs ($\ell \geq 2$) of possible matching points $a_i = (x_{a_i}, y_{a_i}) \leftrightarrow b_i = (x_{b_i}, y_{b_i})$ for $i = 1, \dots, \ell$, then the affine transformation T that gives the best least-square match that minimizes $\sum_{i=1}^{\ell} \|T(a_i) - b_i\|^2$, which is denoted by $\bar{r} = (t_x, t_y, S \cos \theta, S \sin \theta)^t$, is given by [14]:

$$\bar{r} = \frac{1}{\det} \begin{bmatrix} l_A & 0 & -\mu_{X_A} & \mu_{Y_A} \\ 0 & l_A & -\mu_{Y_A} & -\mu_{X_A} \\ -\mu_{X_A} & -\mu_{Y_A} & \ell & 0 \\ \mu_{Y_A} & -\mu_{X_A} & 0 & \ell \end{bmatrix} \begin{bmatrix} \mu_{X_B} \\ \mu_{Y_B} \\ l_{A+B} \\ l_{A-B} \end{bmatrix}, \quad (2)$$

where

$$\mu_{X_A} = \sum_i^{\ell} x_{a_i}, \quad \mu_{X_B} = \sum_i^{\ell} x_{b_i}, \quad \mu_{Y_A} = \sum_i^{\ell} y_{a_i}, \quad \mu_{Y_B} = \sum_i^{\ell} y_{b_i}, \quad (3)$$

$$l_{A+B} = \sum_i^{\ell} (x_{a_i}x_{b_i} + y_{a_i}y_{b_i}), \quad l_{A-B} = \sum_i^{\ell} (x_{a_i}y_{b_i} + y_{a_i}x_{b_i}), \quad l_A = \sum_i^{\ell} (x_{a_i}^2 + y_{a_i}^2), \quad (4)$$

$$\det = \ell \cdot l_A - \mu_{X_A}^2 - \mu_{Y_A}^2. \quad (5)$$

71 This transformation is used by Van Wamelen et al. [12] considering as possible matches those points with $\|T(a_i) - b_k\| <$
72 $\gamma = R_Q/n$ for some a_i and b_k neighbors of p_i and q_k , with R_Q being the minimum disk radius that covers the points in
73 \mathcal{Q} . This process continues until a higher number of matches is achieved.

74 Finally, some approaches implement correspondence matrices with the possibility of outliers from both sets. For
75 instance, the Thin Plate Spline Robust Matching (TPS-RPM) reported by Chui & Rangarajan [10], and the revised
76 version of Yang [15] using a double-sided approach to manage the outliers under a reduced optimization approach,
77 which use an annealing temperature process to solve the optimization problem. Consider a correspondence matrix
78 $\mathbb{C} = [c_{ik}]$ with dimensions $n \times m$ that indicates the probability of matching each $p_i \in \mathcal{P}$ with each $q_k \in \mathcal{Q}$. This approach
79 includes two possible outliers vectors r and s with dimensions $(n \times 1)$ and $(1 \times m)$, respectively, associated with the
80 defects that could not be matched in the optimization problem shown in Eq. 6. In this objective function, α and λ are
81 controlling parameters to avoid classifying every point as an outlier (later used in the annealing heuristic), $\mathcal{L}T$ is the
82 thin-plate splines smooth regularization, and \mathcal{T} is the temperature parameter of the annealing process beginning at \mathcal{T}_o
83 and decreasing in each iteration.

$$\begin{aligned} & \underset{\mathbb{C}, r, s, T}{\operatorname{argmin}} \sum_{i=1}^n \sum_{k=1}^m c_{ik} \|q_k - T(p_i)\|^2 + \lambda \mathcal{L}T - \alpha \sum_{i=1}^n \sum_{k=1}^m c_{ik} + \mathcal{T} \sum_{k=1}^m \sum_{i=1}^n c_{ik} \log c_{ik} \\ & \text{subjected to } 0 \leq c_{ik}, r_i, s_k \leq 1, \quad \forall i = 1, \dots, n, \quad \forall k = 1, \dots, m \\ & \sum_{k=1}^m c_{ik} + r_i = 1, \quad \forall i = 1, \dots, n \\ & \sum_{i=1}^n c_{ik} + s_k = 1, \quad \forall k = 1, \dots, m \end{aligned} \quad (6)$$

84 The annealing process helps to solve this optimization problem by approximating the values of the correspondence
85 matrix and the outlier vectors, given a fixed transformation T following Eq 7 to 9. Here, u_c and v_c are the centers
86 of mass of both sets. The approximated version of c_{ik}, s_k , and r_i are finally implemented to obtain the optimal affine
87 transformation.

$$c_{ik} = \frac{1}{\mathcal{T}} \exp \left[\frac{\alpha}{\mathcal{T}} - \frac{(q_k - T(p_i))^t (q_k - T(p_i))}{\mathcal{T}} \right], \forall i = 1, \dots, n, \quad \forall k = 1, \dots, m \quad (7)$$

$$r_i = \frac{1}{\mathcal{T}_o} \exp \left[-\frac{(u_c - T(p_i))^t (u_c - T(p_i))}{\mathcal{T}_o} \right], \forall i = 1, \dots, n \quad (8)$$

$$s_k = \frac{1}{\mathcal{T}_o} \exp \left[-\frac{(q_k - v_c)^t (q_k - v_c)}{\mathcal{T}_o} \right], \forall k = 1, \dots, m \quad (9)$$

88 3. Matching alternatives in corrosion pipelines: main drawbacks

89 The alternatives shown in the previous section address the general problem of point matching, which usually deals
90 with image recognition like fingerprints or distortion for 3-D shapes; see, for instance, [9, 15]. This problem has also
91 been reported for matching defects in consecutive inspections as an alternative of matching learning approaches using
92 Support Vector Machines (SVM), decision trees, and random forest [16]. In this direction, Dann & Dann [11] adopted
93 the approach of Yang [15] of the correspondence matrix and outlier vectors in Eq. 6.

94 The approach of Dann & Dann divides the pipeline into fixed segments that overlap every 0.3 m at the joints,
95 using the points mapped into a 2D plane by unrolling the pipeline in the axial direction. The plane uses an extended
96 version by duplicating half segments on each side, as shown in Fig. 2 to account for the pipeline continuity in the
97 circumferential direction and to prevent any biased misclassification. This figure illustrates how those defects located
98 from 06:00 hr to 12:00 hr (and from 00:00 to 06:00) duplicate at -06:00 hr to 00:00 hr (at 12:00 hr to 18:00 hr,
99 respectively). Dann & Dann used an alternative version of Eq. 1 by projecting the defects in both sets to the plane
100 $z = 1$, i.e., $a = (x_a, y_a, 1)$ and $b = (x_b, y_b, 1)$ for any $a \in \mathcal{P}$ and $b \in \mathcal{Q}$, and using a 3×3 affine transformation T_3 ,

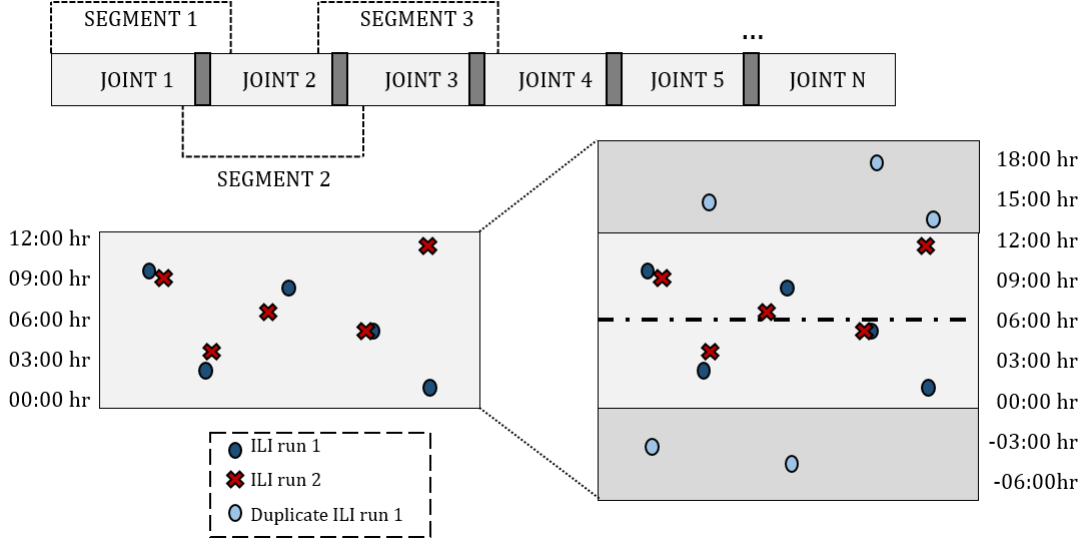


Figure 2: Scheme of the proposed matching by Dann & Dann [11].

101 whose components $t_{11}, t_{12}, t_{21}, t_{22}$ are associated with the scaling and rotation, t_{13}, t_{23} with the translation, and the last
 102 row vector is $[0, 0, 1]$ just to maintain the points in the same plane.

The optimization problem acknowledges the duplicates of the defects by augmenting the matrix c_{ik} and the vector r_i to $(2n \times m)$ and $(2n \times 1)$, respectively. This approach seeks for affine transformations that are not very different from I_3 (the identity 3×3 matrix) by using a controlling parameter β_c as follows $\beta_c \text{Tr}[(T_3 - I_3)^l (T_3 - I_3)]$, where $\text{Tr}[A]$ is the trace of matrix A . The final optimization problem is shown in Eq. 10, which is solved using again the annealing process with the temperature decreasing by $\mathcal{T} = \mathcal{T}_0 \gamma^l$ with $\gamma \leq 1$ and l being the iteration step.

$$\begin{aligned}
 & \underset{\mathcal{C}, r, s, T_3}{\text{argmin}} \sum_{i=1}^{2n} \sum_{k=1}^m c_{ik} \|q_k - T_3(p_i)\|^2 - \alpha \sum_{i=1}^{2n} \sum_{k=1}^m c_{ik} + \beta_c \text{Tr}[(T_3 - I_3)^l (T_3 - I_3)] \\
 & \text{subjected to } 0 \leq c_{ik}, r_i, s_k \leq 1, \quad \forall i = 1, \dots, 2n, \quad \forall k = 1, \dots, m \\
 & \sum_{k=1}^m c_{ik} + r_i = 1, \quad \forall i = 1, \dots, 2n; \\
 & \sum_{i=1}^{2n} c_{ik} + s_k = 1, \quad \forall k = 1, \dots, m
 \end{aligned} \tag{10}$$

103 This formulation seems adequate for the matching of consecutive inspections given that it considers the possibility
 104 of outliers in both sets, it seeks for a probability of matching (known as *Soft-assign*), and it prevents the trivial solution
 105 of $[c_{ik}] = \mathbf{0}$ by including the term $\alpha \sum_{i=1}^{2n} \sum_{k=1}^m c_{ik}$. The matching approach depends on the selection of α and β_c ,
 106 where α could be linked to the outliers proportion in both sets, and β_c is a penalization parameter associated with
 107 the transformation deviation [11]. This approach assumes that both parameters are known, and the authors proposed
 108 the following feasible values: $\alpha \in [0, 0.1]$ and $\beta_c \geq 200\mathcal{T}$. However, it is noteworthy that possible matches can be
 109 misclassified as outliers by forcing a final transformation to be nearly the same as the identity matrix or assigning
 110 a lower correspondence. According to Dann & Dann, this correspondence should be greater than 0.9 to classify as
 111 a positive match. For illustrative purposes, consider the same example used in the work of Dann & Dann, and also
 112 the subset of pairs (p_i, q_k) with $p_i \in \mathcal{P}$ and $q_k \in \mathcal{Q}$ such that the nearest neighbor of p_i is q_k and vice versa. Figure
 113 3 depicts the corresponding results based on the approach of Dann & Dann with annealing, where ILI 1 and ILI
 114 2 depict the position from the two consecutive inspections and ILI 1 mod is the results after applying the annealing
 115 method. Note that the approach achieves a clear and good matching result when there is a marked affine transformation

116 (Figure 3a), in this case, a diagonal displacement in the upper right direction. However, Figure 3b shows a clear case
 117 when the transformation is barely different from the identity matrix producing a significant misclassification. The
 118 correspondence and outliers results, in this case, indicate that only 7 over 21 defects could be matched, while in the
 119 previous, case almost all of them could be paired.

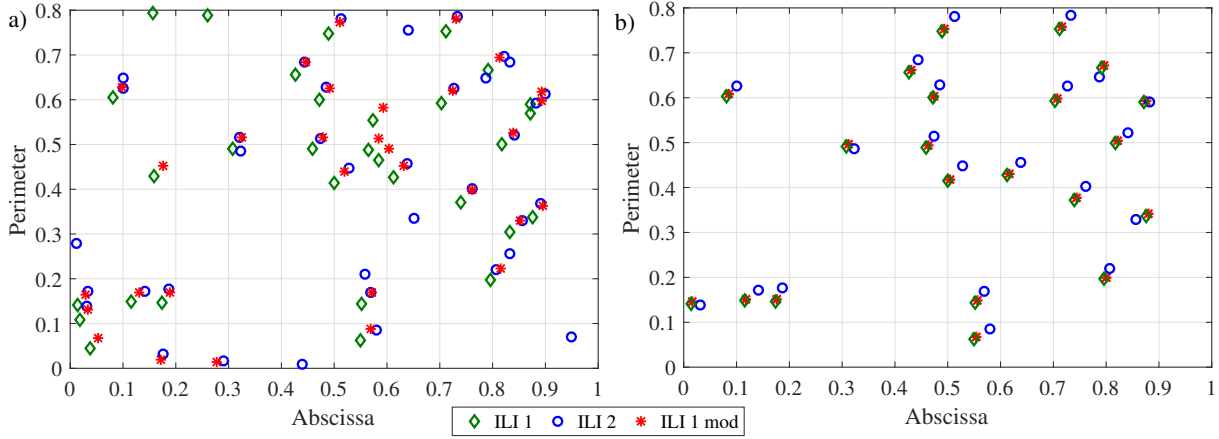


Figure 3: Point matching results with a) the example of Dann & Dann and b) a subset of points with the crossed nearest neighbors.

120 The point matching problem for corroding pipelines goes beyond only the affine transformation. The physical
 121 explanation of this mismatching comes from the fact that the reported defects are subjected to location uncertainties
 122 in both the axial and circumferential directions, which can be thought of as a calibrating uncertainty of the defect's
 123 position, as remarked by Pakrashi et al. [17]. Let (x, y) denote a defect, this defect would actually lie in the region
 124 $(x \pm \delta_x, y \pm \delta_y)$, where δ_x and δ_y depend on the inspection tool. For instance, following the reported by an inspection
 125 vendor [18], it can be assumed that $\delta_x = 0.1m$ and $\delta_y = 10^\circ$ (i.e., $\frac{\pi D}{36}$, where D is the pipeline diameter). In this regard,
 126 two possible criteria can be used to identify possible matches using the region formed by $(x \pm \delta_x, y \pm \delta_y)$ or the ball
 127 centered at each defect with radius $\sqrt{\delta_x^2 + \delta_y^2}$, as shown in Figure 4. Note that ball radius can be computed only when
 128 δ_x and δ_y have the same units.

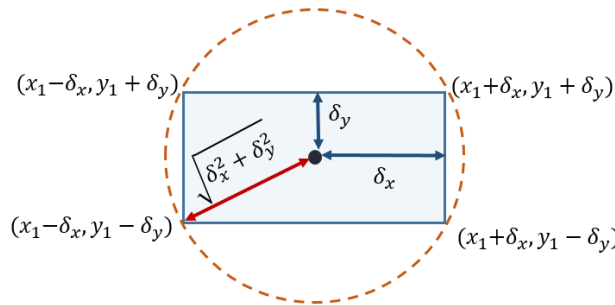


Figure 4: Location uncertainty of a defect given an axial δ_x and circumferential δ_y uncertainties position

129 Overall, the matching problem of corroding pipelines should also consider that some defects already have good
 130 pairing, while others relate to their nearest neighbors. Figure 5 illustrates this case using a real segment in the inner
 131 wall once the approach of Dann & Dann is applied again. This figure shows some defects with suitable preliminary
 132 matches (e.g., between km 5654 and 5655) that produce transformation with very low correspondence probabilities.
 133 This matching may be improved by omitting already detected matches, but this preprocessing would require significant
 134 manual feature selection that seeks to be avoided.

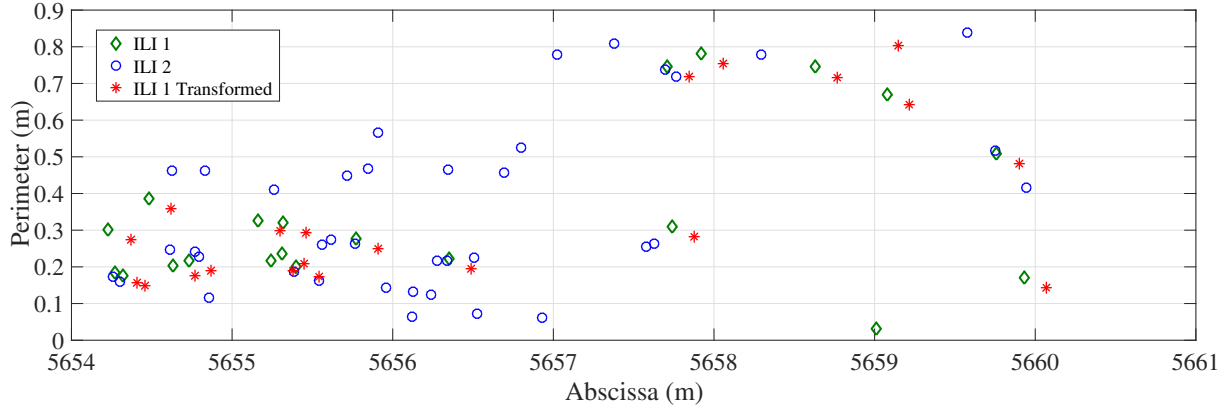


Figure 5: Possible mismatching with the approach of Dann & Dann [11].

135 4. Proposed approach using a Voronoi partition

136 This work proposes a simple approach to match the corrosion defects based on the nearest neighbor criterion
 137 between two inspections, including the possibility of outliers. For this purpose, this approach uses Voronoi cells to
 138 filter possible preliminary matches between the two inspections. Given a set of points $P = \{p_1, \dots, p_n\}$ in \mathbb{R}^2 , the
 139 Voronoi cell of p_l (\mathcal{V}_l) is defined by the subset of points in \mathbb{R}^2 such that the nearest point in P is p_l . For a more formal
 140 definition consider the Euclidean metric in \mathbb{R}^2 $d(p, q) = \sqrt{(x_p - x_q)^2 + (y_p - y_q)^2}$, then $\mathcal{V}_l = \{x \in \mathbb{R}^2 | d(x, p_l) \leq$
 141 $d(x, p_i), \forall i \neq l\}$. The use of the Voronoi cells allows identifying the nearest neighbors between the points of \mathcal{P} and \mathcal{Q}
 142 quickly, as is illustrated in Figure 6. This figure depicts the Voronoi polygons given a query, which is the closest point
 143 of \mathcal{P} or \mathcal{Q} .

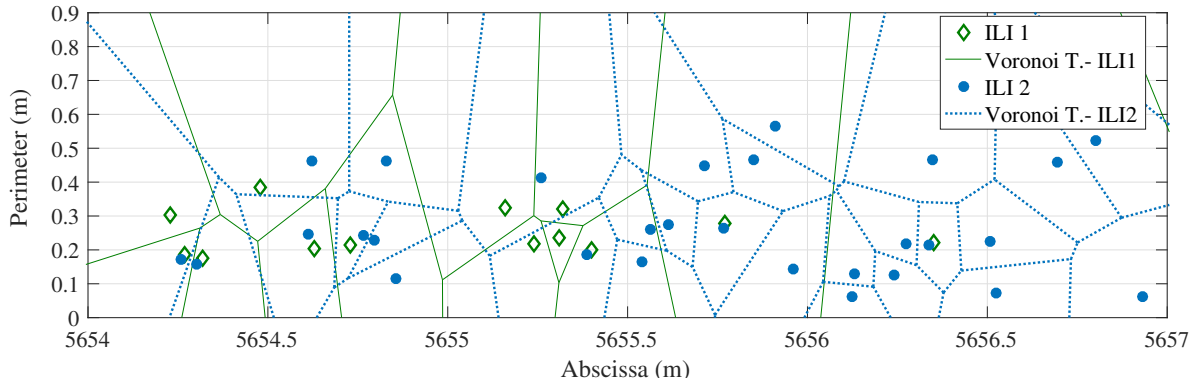


Figure 6: Voronoi tessellations from the case shown in Figure 5.

144 Based on the mentioned above, the approach proposes three stages to identify possible matches between two
 145 consecutive inspections (Figure 7). First, defects from two consecutive ILI measurements are preprocessed by deter-
 146 mining their crossed nearest neighbors. Second, these nearest neighbors are implemented in an iterative process to
 147 estimate matching transformation until the transformed data converges in each iteration. Finally, the transformation
 148 determines the correspondence matrix and outliers vectors. This approach will be described in detail below¹.

¹Note that this type of multistage approach has also been reported in defect detection [19] and spatial statistics [20]

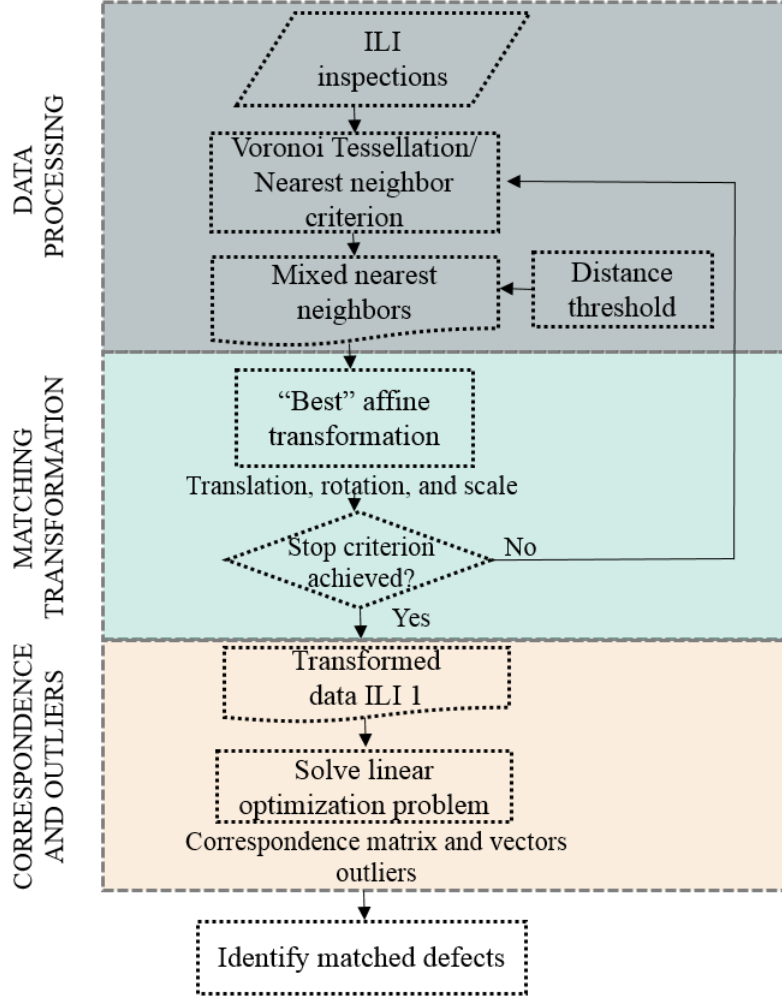


Figure 7: Proposed methodology for defects matching

149 4.1. Data processing

150 The data processing starts by duplicating each defect of the first inspection (ILI 1), as depicted in Figure 2.
 151 This duplication aims to account for the pipeline continuity in the circumferential direction, i.e., ensuring that those
 152 points at 12:00 hr continue in the 0:00 hr. Denote the number of final points in the first inspection by $2n$ and m
 153 for the second. The Voronoi cells $\mathcal{V}_1^1, \dots, \mathcal{V}_{2n}^1$ and $\mathcal{V}_1^2, \dots, \mathcal{V}_m^2$ are determined iteratively following any available
 154 method. Some of the common methods include the Plane-sweep, the tree expansion & deletion algorithm, or iterative
 155 approaches evaluating the dual diagram, i.e., the Delaunay Triangulation [21, 22]. This work considers the latter
 156 approach based on the functions included in the R-project package *deldir* for Delaunay Triangulation and Dirichlet
 157 (Voronoi) Tessellation. These Voronoi cells are required to be assigned to a unique tile list from 0 to $2n$ (0 to m ,
 158 respectively) for the first (second) inspection to identify the tiles containing each mixed point, i.e., points sharing
 159 being the nearest neighbors, as illustrated in Figure 8. Denote by T_{11} and T_{12} the tile list of the mixed points, and $T_{\mathcal{V}^1}$
 160 and $T_{\mathcal{V}^2}$ as the $2n \times m$ matrices version of these lists, as the form of an indicator matrix. For instance, if the first entry
 161 of T_{11} is s then the first row of $T_{\mathcal{V}^2} = e_s$, where e_s is the standard unit vector of m positions with 1 in the s^{th}
 162 and elsewhere zero. Similarly, if the first entry of T_{12} is r , then the first column of $T_{\mathcal{V}^1} = e_r$ with 1 in the r^{th} position.
 163 The preliminary mixed nearest neighbors are determined by the Hadamard product or the element-wise product, i.e.,
 164 $T_{\mathcal{V}} := (T_{\mathcal{V}^1} \odot T_{\mathcal{V}^2})_{ij} = (T_{\mathcal{V}^1})_i (T_{\mathcal{V}^2})_j$, and by considering only those pairs of defects where $d(p_i, q_k) < \delta$ where δ is

165 defined by $\delta = \sqrt{\delta_x^2 + \delta_y^2}$ or by the vector (δ_x, δ_y) as illustrated in Figure 4. Denote the set of nearest neighbors by
 166 (p_i, q_i) for $i = 1 : \ell \leq \min(2n, m)$, and select from the original points or the duplicate those with the lower nearest
 167 neighbor distance.

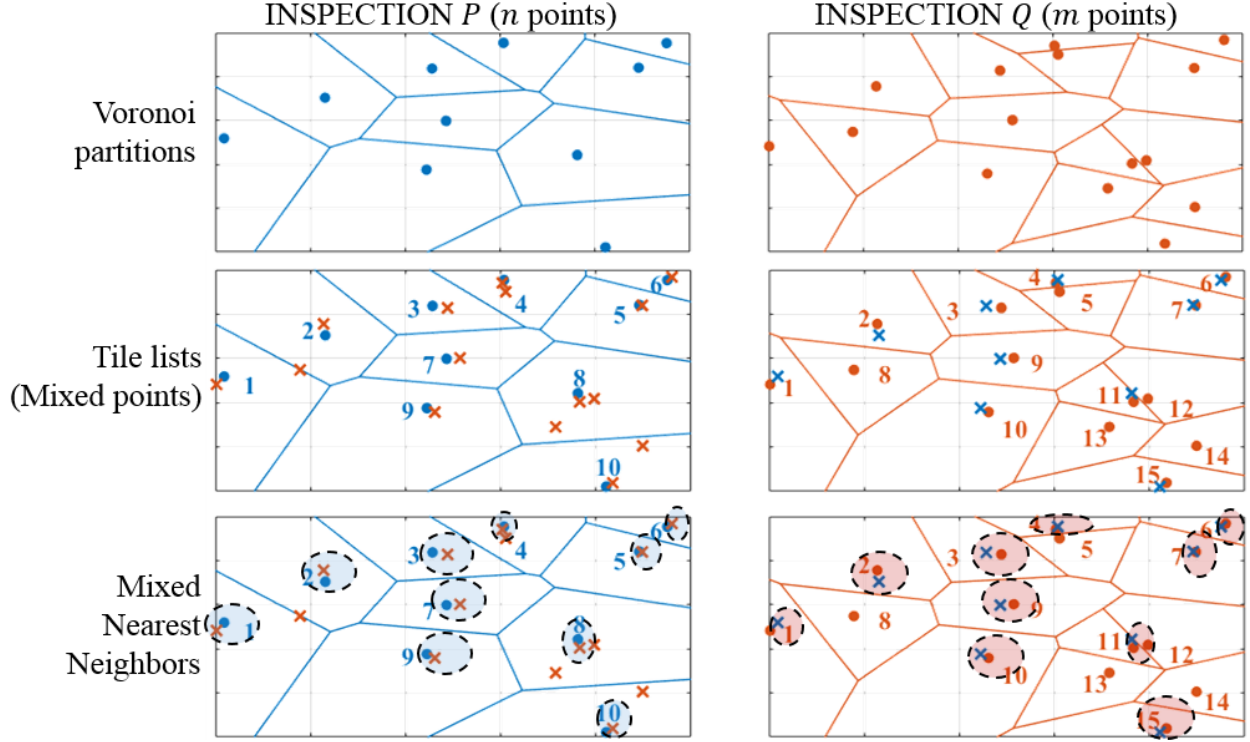


Figure 8: Scheme of the data processing.

168 4.2. Matching transformation approach

169 The second stage seeks the best feasible transformation given the initial mixed nearest neighbors obtained from
 170 both Voronoi cells. For this purpose, an iterative method is implemented following a similar procedure as reported by
 171 Besl & McKay in the Iterative Closest Point (ICP) [9]. First, the nearest neighbors are determined using the Voronoi
 172 cells, then the best affine transformation is determined following the optimal transformation reported by Chang et
 173 al. [14] and shown in Eq. 2. This transformation is applied to the data from the first inspection, and the iterative
 174 process finishes when the mean square error (MSE) of the matchings between two consecutive iterations is shorter to
 175 a predefined threshold, i.e., if $d^k = \sum_{i=1}^{\ell} \|p_i - q_i\|^2$ for the k^{th} iteration, then the stopping criterion is achieved when
 176 $\tau > \min(d^k - d^{k+1}, d^{k+1})$.

177 4.3. Correspondence and outliers optimization approach

178 The final matches are identified following the correspondence matrix and vector outliers. Given the affine transfor-
 179 mation T_3 in Eq. 10, the optimization problem turns into linear programming with linear constraints, as shown in Eq.
 180 11, where $w_{ik} = \|q_k - T_3(p_i)\|^2$, which may be limited to a binary solution indicating the matches and the classification
 181 as outliers in both sets [15]. Several methods can solve this linear optimization problem, but this approach uses linear
 182 programming following the package *lpSolve* of R-project due to its simplicity. Other approaches can be studied like a
 183 Benders Decomposition Method (BDM), which is an approach with an increasing interest in the field of optimization
 184 for both Linear (LP) and Mixed-Integer Linear Programming (MILP) problems; however, it is out of the scope of this
 185 work.

$$\begin{aligned}
& \underset{\mathbb{C}, r, s}{\operatorname{argmin}} \sum_{i=1}^{2n} \sum_{k=1}^m c_{ik} (w_{ik} - \alpha) \\
& \text{subjected to } 0 \leq c_{ik}, r_i, s_k \leq 1, \quad \forall i = 1, \dots, 2n, \quad \forall k = 1, \dots, m \\
& \sum_{k=1}^m c_{ik} + r_i = 1, \quad \forall i = 1, \dots, 2n \\
& \sum_{i=1}^{2n} c_{ik} + s_k = 1, \quad \forall k = 1, \dots, m
\end{aligned} \tag{11}$$

186 5. Spatial dependencies of the case study

187 5.1. Main parameters

188 The case study concerns an API 5LX52 pipeline 45km long with six main vales; its height lies between 2560 to
189 2660m above sea level. Near kilometer 33, there is a river crossing, whereas the last 10km are close to urban zones.
190 The pipeline has a nominal wall thickness of 6.35mm and an external diameter of 273.1mm. The analysis presented
191 here was based on data obtained from two consecutive ILI measurements two years apart. According to the ILI report,
192 this diameter is maintained along the entire abscissa, while the wall thickness exhibits greater variability due to the
193 location of welded covers, valves, dents, and manufacturing flaws. For further details, please refer to Amaya-Gómez
194 et al. [23]. Table 1 shows a broad classification of the soil along the pipeline following the taxonomy of the USDA
195 (United States Department of Agriculture). The pipeline has a bituminous coating of coal tar and an impressed current
196 cathodic protection (ICCP) system.

Table 1: Pipeline segmentation based on the USDA soil classification

| Segment* | Category | Classification | ID |
|---------------|-------------|---|--------|
| 0.00-6.66km | Complex | Pachic Melanudands (50%), Andic Dystrudepts (20%), Aerice Endoaquepts (15%), Aquic Hapludands (15%) | Soil 1 |
| 6.66-8.2km | Association | Humic Lithic Eutrudepts (35%), Typic Placudands (25%), Dystric Eutrudepts (25%) | Soil 2 |
| 8.2-9.66km | Complex | Pachic Melanudands (50%), Andic Dystrudepts (20%), Aerice Endoaquepts (15%), Aquic Hapludands (15%) | Soil 1 |
| 9.66-11.61km | Association | Humic Dystrudepts (60%), Typic Hapludalfs (40%) | Soil 3 |
| 11.61-13.48km | Complex | Pachic Haplustands (35%), Humic Haplustands (35%), Fluventic Dystrudepts (30%) | Soil 4 |
| 13.48-14.86km | Association | Aerice Epiaquepts (60%), Fluvaqueptic Endoaquepts (40%) | Soil 5 |
| 14.86-15.89km | Complex | Humic Dystrudepts (40%), Typic Haplustalfs (35%), Fluvaqueptic Endoaquepts (25%) | Soil 6 |
| 15.89-17.62km | Association | Aerice Epiaquepts (60%), Fluvaqueptic Endoaquepts (40%) | Soil 5 |
| 17.62-18.65km | Complex | Humic Dystrudepts (40%), Typic Haplustalfs (35%), Fluvaqueptic Endoaquepts (25%) | Soil 6 |
| 18.65-18.84km | Association | Typic Endoaquepts (40%), Aerice Endoaquepts (30%), Thaptic Hapludands (20%) | Soil 7 |
| 18.84-21.40km | Complex | Humic Dystrudepts (40%), Typic Haplustalfs (35%), Fluvaqueptic Endoaquepts (25%) | Soil 6 |
| 21.40-22.63km | Association | Typic Endoaquepts (40%), Aerice Endoaquepts (30%), Thaptic Hapludands (20%) | Soil 7 |
| 26.07-27.35km | Complex | Pachic Haplustands (35%), Humic Haplustands (35%), Fluventic Dystrudepts (30%) | Soil 4 |
| 27.35-28.22km | Urban zone | - | - |
| 28.22-30.52km | Association | Aerice Epiaquepts (60%), Fluvaqueptic Endoaquepts (40%) | Soil 5 |
| 30.52-33.10km | Complex | Pachic Haplustands (35%), Humic Haplustands (35%), Fluventic Dystrudepts (30%) | Soil 4 |
| 33.10-35.45km | Association | Typic Endoaquepts (40%), Aerice Endoaquepts (30%), Thaptic Hapludands (20%) | Soil 7 |
| 35.45-45.00km | Urban zone | - | - |

*Both ILI did not include information of the segment from 22.63 to 26.07km

197 The defects measuring tool was a Magnetic Flux Leakage (MFL). Based on information reported in Amaya-
198 Gómez et al. [24] about the inspection vendor, it can be assumed a circumferential uncertainty of 5° during the
199 inspection. The measurement uncertainties of the defect depth, length, and width are given by $d_{ILI} = d_{real} \pm \epsilon_d$,
200 $l_{ILI} = l_{real} \pm \epsilon_l$, and $w_{ILI} = w_{real} \pm \epsilon_w$, where $d_{ILI}, l_{ILI}, w_{ILI}$ stand for the depth, length, and width reported by the ILI
201 tool, and $\epsilon_d, \epsilon_l, \epsilon_w$ are the measurement errors. The measurement errors can be assumed to follow normal distributions
202 centered at 0 with standard deviations obtained from the inspection vendors [25]. It is reasonable to assume that these
203 standard deviations are as follows: $\sigma_{\epsilon_d} = 0.1 t$ with t the nominal wall thickness, $\sigma_{\epsilon_l} = \sigma_{\epsilon_w} = 11.70\text{mm}$, considering a

length and width accuracy of 15mm with a confidence of 80% of the data. For confidential agreements, further details of the case study cannot be provided.

5.2. Main descriptors of corrosion defects

A summary statistics of these data sets is depicted in Table 2 with the mean value and the coefficient of variation (CoV) of all the reported defects per inspection and pipe wall. Because further information about defects shape is not available in ILI, the maximum rather than the average depth for each defect will be considered from now on. Note that Table 2 show a higher CoV for the outer wall than in the inner wall that can be explained by the higher variability of corrosion factors in the soil than inside in the pipe [6].

Table 2: Summary of corrosion defects along the abscissa

| Parameter | Mean (Coefficient of Variation) | | | |
|--------------------|---------------------------------|------------------|------------------|------------------|
| | ILI-1 Inner wall | ILI-2 Inner wall | ILI-1 Outer wall | ILI-2 Outer wall |
| Average depth (%t) | 5.49 (0.26) | 5.29 (0.27) | 7.28 (0.49) | 6.77 (0.46) |
| Maximum depth (%t) | 11.54 (0.21) | 11.14 (0.19) | 15.84 (0.46) | 14.62 (0.43) |
| Length (mm) | 26.07 (0.49) | 26.07 (0.43) | 28.07 (0.48) | 27.37 (0.44) |
| Width (mm) | 22.5 (0.40) | 25.92 (0.53) | 28.81 (0.67) | 32.60 (0.75) |
| Number of defects | 23708 | 43399 | 2862 | 4264 |

6. Matching results and New defects identification

6.1. Matching implementation example

For a better understanding of the matching approach, the segment shown in Figure 6 is used as an example to illustrate how the matches are determined and what are the “farther matches”. As mentioned in Section 4, data processing starts determining the Voronoi cells for each of the corrosion points in both inspections. Consider the example shown in Figure 6 with $n = 13$ and $m = 29$, the number of points in sets \mathcal{P} and \mathcal{Q} . Figure 9 depicts this example, including Voronoi tile identification from 1 to 13, for the first inspection and 1 to 29 for the second. In this example, duplication is unnecessary, considering that none of the points in ILI1 were located near the border.

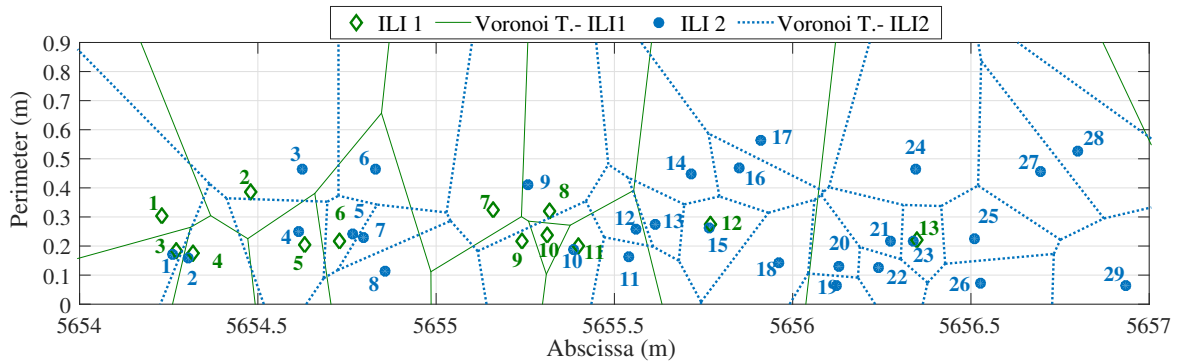


Figure 9: Voronoi tessellations and tile identification - Continuing Figure 6.

The tile list of the mixed points, i.e., the nearest neighbor in the other inspection, for the first thirteen positions are given as follows:

$$T_{11} = \{1, 3, 1, 2, 4, 5, 9, 8, 10, 10, 10, 15, 23\}, \quad (12)$$

$$T_{12} = \{3, 4, 2, 5, 6, 6, 6, 6, 8, 11, 11, 11, 12, \dots\}. \quad (13)$$

Consequently, the 13×29 matrix version of these lists, which are determined using row and column standard unit vectors (i.e., $e_i = [0, \dots, 1, \dots, 0]$ at i^{th} position) follows:

$$T_{\mathcal{V}^1} = \begin{bmatrix} | & | & | & | & | & \dots \\ e_3 & e_4 & e_2 & e_5 & e_6 & \dots \\ | & | & | & | & | & \dots \end{bmatrix}, \quad T_{\mathcal{V}^2} = \begin{bmatrix} \text{---} & e_1 & \text{---} \\ \text{---} & e_3 & \text{---} \\ \text{---} & e_1 & \text{---} \\ \text{---} & e_2 & \text{---} \\ \vdots & & \end{bmatrix}$$

220 Note that the each unit vector e_i in $T_{\mathcal{V}^1}$ have dimension 1×13 , whereas each unit vector in $T_{\mathcal{V}^2}$ 29×1 . The mixed
 221 nearest neighbors are determined by the element-wise product of $T_{\mathcal{V}^1}$ and $T_{\mathcal{V}^2}$ with their non-zero elements. In this
 222 example, the sparse version of this matrix, i.e., the non-zero positions, are given by $T_{\mathcal{V}} = \{(2,3), (3,1), (4,2), (5,4),$
 223 $(6,5), (8,9), (11,10), (12,15), (13,23)\}$, where the first position is associated with the points in ILI 1 and the second in
 224 ILI 2 that are mixed nearest neighbors. For instance, note in Figure 9 that the seventh and eighth points of ILI 1 are
 225 the closest points to the ninth point in ILI 2, but the latter is the nearest neighbor, which leads to the mixed point (8,9).
 226 These nine pairs are initially used in the optimal transformation reported by Chang et al. [14] and shown in Eq. 2.
 227 Afterward, the mixed nearest neighbors and the optimal transformation are determined iteratively until the stopping
 228 criterion of $\tau = 0.001 > \min(d^k - d^{k+1}, d^{k+1})$ is achieved, where recall that d^k is the matching MSE for the k^{th} iteration.
 229 Considering a separation greater than $\delta = \sqrt{\delta_x^2 + \delta_y^2} = 0.11m$, the final results correspond with all the mixed nearest
 230 neighbors reported at $T_{\mathcal{V}}$, except from the (2,3) pair.

231 Figure 10 shows the obtained results for the complete segment of seven meters long that was previously used for
 232 the annealing method (see Figure 5). This figure includes some additional ‘‘farther matches’’, defined as pairs with a
 233 separation greater than δ .

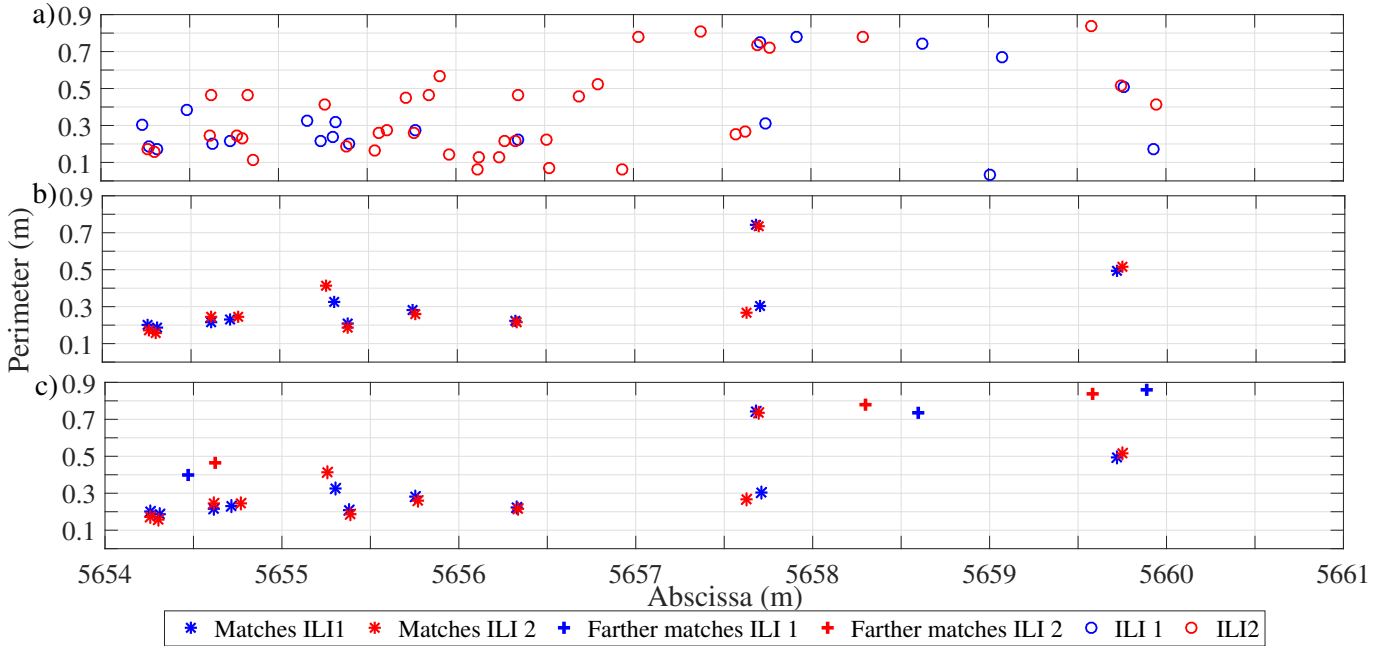


Figure 10: a) Initial ILI data; b) obtained matches by the proposed approach, and c) matches considering farther nearest defects.

234 In this case, Figure 10a depicts the complete segment shown in Figure 5 with the 21 and 39 defects reported for the
 235 first and second inspection, respectively. Figure 10b shows eleven matches determined with the proposed approach
 236 after transforming the data, which contrasts with the zero feasible matches in the annealing case. Finally, Figure 10c
 237 includes three possible additional matches with a larger separation, which should be further monitored. After the
 238 correspondence and outlier approach is implemented (see Eq. 11) with $\alpha = 0.01$, the matches are confirmed, and the

239 farther matches are considered as outliers. This parameter was considered because it obtained a higher true matching
 240 ratio for different synthetic samples.

241 *6.2. Comparison of the proposed matching approach with the Annealing method*

242 Section 4 proposed an alternative matching method based on the Voronoi tessellation and an iterative affine trans-
 243 formation. This approach raised as an alternative of existing methods like the Annealing method proposed by Dann
 244 & Dann [11]. This section compares both approaches using synthetic datasets. Let $n = m = 30$ and consider
 245 $\mathcal{P} := \{(p_{xi}, p_{yi})\}_{i=1}^{30}$ to be uniform random sampled in $[0, 1]^2$ and $\mathcal{Q} := \{(p_{xi} + \Delta_x, p_{yi} + \Delta_y)\}_{i=1}^{30}$ where Δ_x and Δ_y are
 246 uniform random variables associated with the location uncertainties $\delta_x = 0.1$ and $\delta_y = 10^\circ$, i.e., $\Delta_x \sim Unif(-\delta_x, \delta_x)$
 247 and $\Delta_y \sim Unif(-\delta_y, \delta_y)$. Consider 50 random P and Q datasets to compare both approaches using the true matching
 248 ratio. Considering that the annealing process depends on α , β_c and λ (see Section 3), a previous sensibility analysis
 249 was implemented to determine which parameters achieve the highest prediction (Table 3).

Table 3: Sensibility analysis for the annealing matching approach

| Parameter | α | β_c | λ | Matching ratio |
|--------------------------|------------|-------------------|-----------|----------------|
| Analysis of α | $1e^{-05}$ | $200\mathcal{T}$ | 0.96 | 0.339 |
| | $1e^{-04}$ | $200\mathcal{T}$ | 0.96 | 0.342 |
| | $1e^{-03}$ | $200\mathcal{T}$ | 0.96 | 0.388 |
| | $1e^{-02}$ | $200\mathcal{T}$ | 0.96 | 0.608 |
| | $1e^{-01}$ | $200\mathcal{T}$ | 0.96 | 0.614 |
| Analysis of β_c | $1e^{-04}$ | $300\mathcal{T}$ | 0.96 | 0.340 |
| | $1e^{-04}$ | $400\mathcal{T}$ | 0.96 | 0.344 |
| | $1e^{-04}$ | $800\mathcal{T}$ | 0.96 | 0.344 |
| | $1e^{-04}$ | $1000\mathcal{T}$ | 0.96 | 0.342 |
| | $1e^{-04}$ | $2000\mathcal{T}$ | 0.96 | 0.342 |
| Analysis of λ | $1e^{-04}$ | $200\mathcal{T}$ | 0.9 | 0.346 |
| | $1e^{-04}$ | $200\mathcal{T}$ | 0.92 | 0.344 |
| | $1e^{-04}$ | $200\mathcal{T}$ | 0.94 | 0.340 |
| | $1e^{-04}$ | $200\mathcal{T}$ | 0.98 | 0.341 |
| | $1e^{-04}$ | $200\mathcal{T}$ | 0.99 | 0.341 |

250 The results in Table 3 indicate that the matching ratio increases for $\alpha \geq 0.01$, while β_c and λ do not affect the
 251 matching ratio drastically, but $\beta_c \sim 400\mathcal{T}$ and $\lambda = 0.9$ can be considered. For the proposed approach, an $\alpha \geq 0.01$
 252 also obtained the highest true ratio, as is depicted in Figure 11.

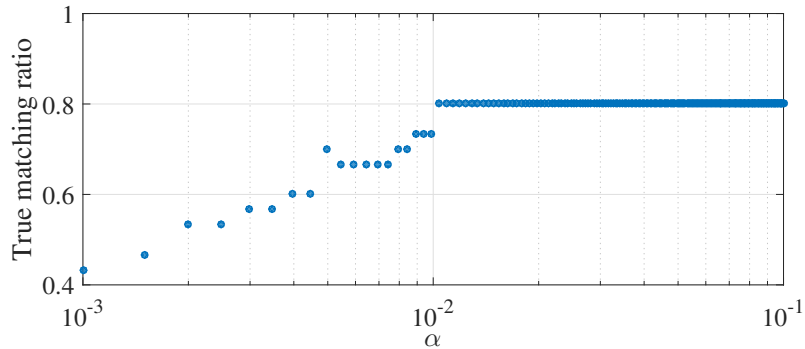


Figure 11: Sensibility analysis of α in the correspondence linear optimization in the proposed approach

253 Based on the above, the correct matching ratio for the annealing process using these parameters and the proposed
 254 approach are compared in Figure 12. This figure includes the results with the annealing process with the parameters

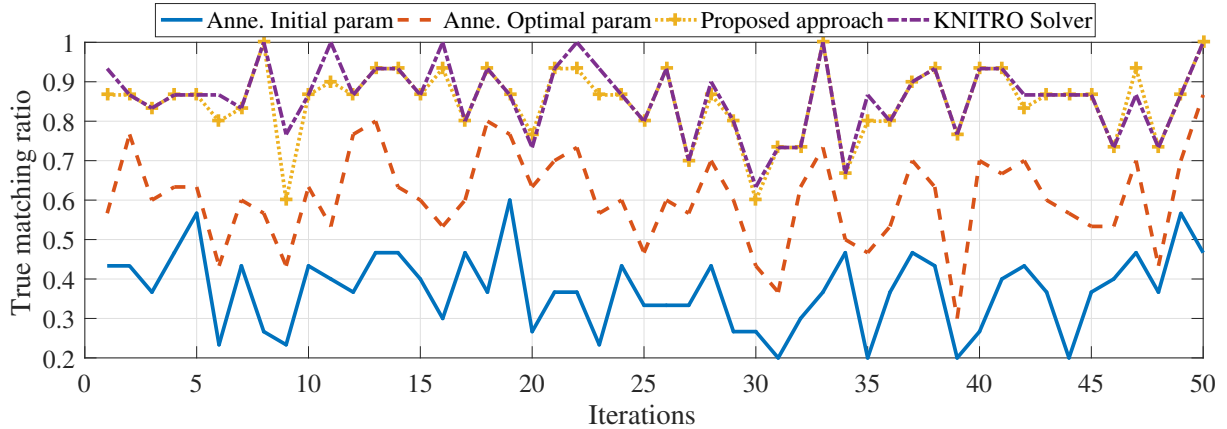


Figure 12: Comparison of the matching ratio of the proposed approach, the annealing method, and using an optimization solver

255 reported by Dann & Dann, i.e., $\alpha = 1e^{-04}$, $\beta_c = 200\mathcal{T}$, and $\lambda = 0.96$, and the one obtained from the sensibility
 256 analysis $\alpha = 0.1$, $\beta_c = 400\mathcal{T}$, and $\lambda = 0.9$.

257 The results indicate that the proposed approach outperforms the annealing matching almost in every case. The true
 258 mean matching for the proposed approach was 0.848 against 0.607 for the annealing process. Figure 12 also displays
 259 the true matching ratio for the solver KNITRO, which is a solver specialized for non-linear optimization problems.
 260 For this case, the optimization problem in Eq. 10 was solved using the NEOS server under an AMPL language with
 261 the parameters obtained from the sensitivity analysis. The results show similar results to those in the KNITRO solver.
 262 However, it should be highlighted that the Voronoi approach does not require any specific optimization software as
 263 in the case of AMPL, nor using a specific server or having a software license to obtain the corrosion matches. The
 264 results were obtained using the open-source software R-project, but other software alternatives are available (e.g.,
 265 Python), which facilitates the implementation in practical applications. The proposed approach represents an interest-
 266 ing alternative for corroded pipelines based on its independence from the controlling parameters in the annealing case.
 267 Although the nearest-neighbor criterion could be affected by possible clusters (or closed neighbors), the obtained re-
 268 sults suggest that the matching ratio was higher than in the annealing case. The latter, considering that the proposed
 269 approach focuses on an affine transformation and incorporates potential location uncertainties in both directions. This
 270 statement should be further confirmed with other synthetic and real datasets considering clustered and dispersed point
 271 patterns.

272 6.3. Matched defects and descriptors of new defects

273 The matching results allow classifying each defect as *new* or *old*, where the former refers to those defects reported
 274 only in the second inspection and the latter in both inspections. These new defects can be attributed to a miss-detection
 275 in the first inspection, a possible false alarm in the second inspection, or a purely new defect produced by the soil
 276 aggressiveness or the fluid properties. Straub [26] remarked that determining which is the reason for the appearance
 277 of these *new* defects may be impossible if the real condition of the pipeline is unknown. However, something that is
 278 certain is that there is an “indication” of new defects. This section describes the main features of both *new* and *old*
 279 sets.

280 The iterative approach identified both likely and farther matches in the previous example, i.e., defects with a
 281 separation higher than δ . Let us focus first on how the matching ratio, $\#Matches/Total\ points\ per\ segment$, changes
 282 when the farther pairs are also contemplated. For this purpose, consider only pipe segments between consecutive
 283 joints without purely new defects (or initial mismatching), i.e., where no defects were only reported in the second
 284 inspection, and segments with possible false alarms –only records in the first inspection–. If the farther are included,
 285 the matching ratio increases from 52% to 65% for ILI1-Int and 44% to 51% for ILI2-Int, respectively. The difference
 286 is shorter for the outer wall, with an average increment from 75% to 78% for ILI1-Ext and from 65% to 68% for
 287 ILI2-Ext. Note that the matching ratio decreased for the second inspection because the number of points increased

288 between the two inspections. However, this difference can also be favored by the presence of clustering or “corrosion
 289 colonies”. Considering the clustering criterion of ASME B31G (i.e., $3t$), about 36% and 46% of defects not being
 290 matched in the inner and outer wall are potential clusters. It indicates that the “corrosion colonies” could hide the
 291 location of these corrosion points and classify them as part of a corrosion cluster, and the “indication” is no longer
 292 available.

Table 4: Matching results based on the soil type

| Soil | Matches including farther pairs | | | | Matches without farther pairs | | | | Number of defects* | | | |
|----------|---------------------------------|-------|------------|-------|-------------------------------|-------|------------|-------|--------------------|-------|------------|------|
| | Inner wall | | Outer wall | | Inner wall | | Outer wall | | Inner wall | | Outer wall | |
| | ILI1 | ILI2 | ILI1 | ILI2 | ILI1 | ILI2 | ILI1 | ILI2 | ILI1 | ILI2 | ILI1 | ILI2 |
| S1 | 68.0% | 46.2% | 68.4% | 63.5% | 60.6% | 41.1% | 65.9% | 61.2% | 1550 | 2283 | 405 | 436 |
| S2 | 68.6% | 46.3% | NR | NR | 63.8% | 43.1% | NR | NR | 1584 | 2346 | 0 | 0 |
| S3 | 72.6% | 48.3% | 81.7% | 53.8% | 65.6% | 43.6% | 78.3% | 51.6% | 931 | 1400 | 60 | 91 |
| S4 | 64.6% | 43.5% | 72.3% | 48.5% | 56.0% | 37.7% | 64.6% | 43.3% | 2774 | 4120 | 65 | 97 |
| S5 | 66.3% | 48.6% | 75.0% | 39.1% | 59.3% | 43.5% | 75.0% | 39.1% | 5332 | 7268 | 12 | 23 |
| S6 | 64.4% | 49.1% | 67.9% | 43.2% | 57.9% | 44.2% | 67.9% | 43.2% | 2230 | 2922 | 28 | 44 |
| S7 | 57.6% | 54.2% | 59.7% | 35.1% | 53.8% | 50.7% | 56.1% | 33.0% | 936 | 994 | 1456 | 2478 |
| UZ | 58.4% | 50.5% | 59.1% | 53.0% | 52.0% | 45.0% | 54.9% | 49.3% | 7069 | 8167 | 718 | 800 |
| Complete | 63.1% | 48.6% | 61.7% | 42.8% | 56.6% | 43.5% | 58.1% | 40.3% | 23655 | 30726 | 2763 | 3985 |

NR. No defects reported

*Segments with possible false alarms or mismatches were not considered

293 The matching ratio was also compared with the different soil categories to verify if there is some relationship with
 294 the number of points (Table 4). The results indicate that the matching ratio does not change drastically at the inner
 295 wall despite the number of defects varying significantly in each soil class. For the first inspection, results ranged from
 296 around 60 to 70%, where the S3 soil had a higher rate but fewer defects. The results for the second inspection range
 297 from 40 to 55%. The outer wall presents a more significant variation, which is explained by the low number of defects
 298 in some soil classes. In both cases, the matching ratio would increase around 4 to 5% on average if potential clusters
 299 were omitted, especially soils S1 and S7.

300 The correspondence matrix and outliers identification contemplate all the reported defects per segment joint;
 301 however, only the matches (including the farther distances) and those defects initially not matched with a separation
 302 shorter than $\delta = 0.11m$ were considered. This filter was implemented because the remaining records would not be
 303 physically matched, and it also reduces computational time. Table 5 summarizes the matching results, ratifying 84%
 304 of the preliminary matches, discarding almost all the farther matches, and replacing them with defects initially not
 305 matched. The remaining 16% of preliminary matches were initially classified as outliers. Recall that the optimization
 306 approach in Eq. 11 produces binary outputs, which can be affected by nearly cluster segments; for instance, a defect
 307 with two close neighbors in the second inspection. In this regard, about 30% (and 38%) of the preliminary matches
 308 discarded with the correspondence matrix at the inner (outer, respectively) wall were classified as possible clusters,
 309 considering the ASME B31G grouping criterion again. Bearing in mind this limitation, the *old* defects would include
 310 both the preliminary and the final matches to recognize also the possibility of new defects from the nearest neighbor
 311 perspective.

Table 5: Matching results after applying the correspondence matrix

| Dataset | Inner wall | | Outer wall | |
|------------------------|-------------|-------------|------------|------------|
| | ILI1 | ILI2 | ILI1 | ILI2 |
| Number of defects | 23708 | 43399 | 2862 | 4264 |
| Preliminary matches | 12980 (84%) | 12980 (84%) | 1592 (83%) | 1592 (84%) |
| Farther matches | 1343 (0%) | 1343 (0%) | 95 (5%) | 95 (5%) |
| Correspondence matches | 12200 | 12200 | 1455 | 1455 |
| Final matches | 14314 | 14314 | 1714 | 1714 |

Percentage in parentheses are the matches obtained by the correspondence and outliers stage.

312 The *old* and *new* defects tend to be close together. The majority of *old* defects are separated less than 0.2m from

313 the *new* ones, as depicted in Figure 13, considering the nearest neighbor distance. The nearest *new* defects have an
 314 average depth within 11 to 12%*t* for both pipe walls.

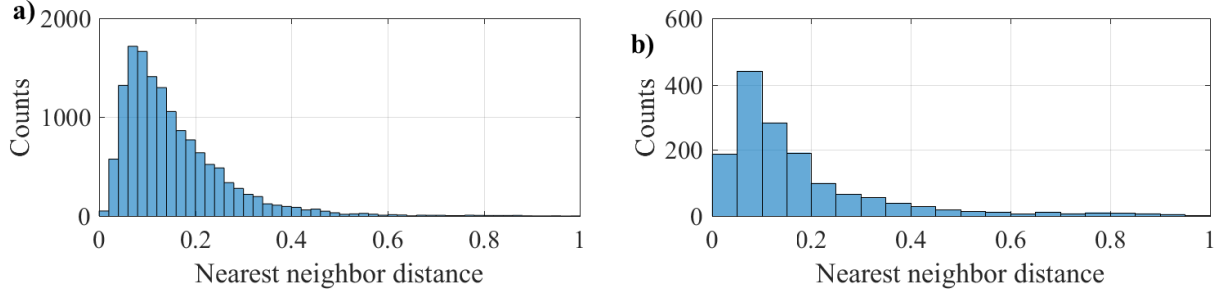


Figure 13: Nearest neighbor distance defects in *old* to *new* set for the a) inner and b) outer walls.

315 Table 6 shows the summary of the corrosion extent from both sets. It can be noticed that larger and wider defects
 316 appeared in the *new* defects' but with shallow depths, associated with uniform corrosion that was not initially detected
 317 in the first inspection.

Table 6: Summary corrosion extent of the *new* and *old* sets

| Set | Parameter | Inner wall | | | | | | Outer wall | | | | | |
|------------|-----------|------------|----|----|-------|----|-----|------------|----|----|-------|----|-----|
| | | Min | Q1 | Q2 | Mean | Q3 | Max | Min | Q1 | Q2 | Mean | Q3 | Max |
| <i>old</i> | Depth | 10 | 10 | 11 | 11.64 | 12 | 36 | 10 | 11 | 14 | 16.8 | 20 | 70 |
| | Length | 10 | 18 | 22 | 25.31 | 30 | 85 | 10 | 19 | 24 | 27.47 | 33 | 109 |
| | Width | 14 | 18 | 20 | 26.82 | 30 | 255 | 16 | 19 | 28 | 35.69 | 41 | 270 |
| <i>new</i> | Depth | 10 | 10 | 10 | 10.89 | 11 | 36 | 10 | 10 | 11 | 13.11 | 14 | 36 |
| | Length | 10 | 18 | 23 | 26.44 | 32 | 92 | 10 | 19 | 25 | 27.3 | 33 | 132 |
| | Width | 12 | 18 | 20 | 25.47 | 28 | 271 | 16 | 18 | 24 | 30.52 | 35 | 813 |

318 7. Insights about the probability of detection and false alarm

319 Besides classifying each defect as *new* or *old*, the matches can be used as indicators of how the probability of
 320 detection (PoD) and the probability of false alarm (PFA) behaved for the inspection tool. Non-destructive Techniques
 321 (NDT) such as ILI deal with the possibility of detecting a corrosion defect given detection threshold, usually associated
 322 with a defect depth of $d^* = 10\%t$, where t stands for the pipeline wall thickness. This detection threshold is used as
 323 a filter to distinguish between defects that can be detected or not, and it is commonly used on one side to define
 324 the probability of detection as $PoD(d) = \mathbb{P}(d > d^*)$ [5]. The filtering process could influence the burst capacity
 325 of the corroded pipeline; however, a threshold of $d^* = 10\%t$ has been indicated to be negligible for this purpose
 326 [27]. The probability of false alarm, on the other side, represents the case of detecting a defect, although it does not
 327 exist and is linked with the noise of the inspection tool. Different researchers have implemented these probabilities
 328 to acknowledge the uncertain number of real defects. For instance, Heidary & Groth [28] proposed a population-
 329 based pitting degradation model that uses the probability of detection and the probability of false alarm (false call)
 330 to estimate the number of existing pits in the ILI measurement and those detected on a second consecutive inspection.
 331 Wang et al. [29] considered the probability of detection at a corroded pipeline rehabilitation process subjected to
 332 seismic activity.

333 Given a particular defect, the false detection would be related to a noise signal that produces a higher response
 334 than the detection threshold. According to Rouhan & Schoefs, these may be attributed to the surrounding conditions
 335 produced by humans' environmental conditions or the measuring process [5]. That was confirmed by Schoefs et al.
 336 [30] with an analysis of human factors accuracy and the use of protocols. These two probabilities are frequently rep-
 337 resented with two separate probability density functions from noise and defect signals, as shown in Figure 14, which

338 sometimes are known as a pure noise signal, and a noise+defect signal [5]. This figure depicts that the probability of
 339 a false alarm is the area under the noise signal's curve. Besides, the probability of detection is determined by the area
 340 under the defect signal. In both cases, after the detection threshold [31].

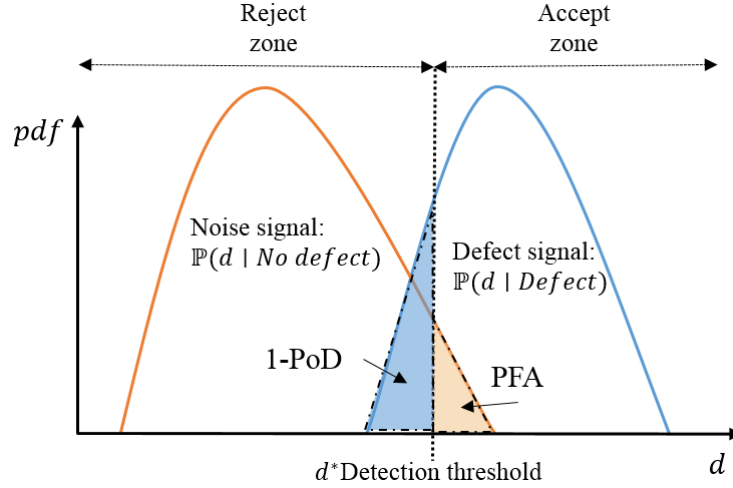


Figure 14: Defect and noise signals scheme

341 In the absence of the inspection signal, let us concentrate on the reported defects from the ILI measurements. If
 342 an ILI measurement occurs, the report would include a certain number of metal loss measurements roughly known as
 343 corrosion defects. These defects have a depth greater than the reporting threshold of 10%t; however, some questions
 344 remain unanswered: (i) Are those detected defects exist? (ii) Is there any undetected defect? These questions can be
 345 translated into the following conditional events given that a defect may be detected or not [5]:

- 346 • E1: absence of a defect, conditioned to no defect detected;
- 347 • E2: absence of a defect, conditioned to defect detected;
- 348 • E3: presence of a defect, conditioned to no defect detected; and
- 349 • E4: presence of a defect, conditioned to defect detected.

Denote the detection output by $d_e(X)$ and the existence of a defect as X . These outputs can be seen in a binary point of view, i.e., $d_e(X), X \in \{0, 1\}$; therefore, $\mathbb{P}(E_1) + \mathbb{P}(E_3) = \mathbb{P}(E_2) + \mathbb{P}(E_4) = 1$. Following this notation, the probability of detection and false alarm can also be defined as $PoD(X) = \mathbb{P}(d_e(X) = 1 | X = 1)$ and $PFA(X) = \mathbb{P}(d_e(X) = 1 | X = 0)$. These definitions were used with the Bayes' conditional theorem by Rouhan & Schoefs to express the previous four conditional events as shown below [5]:

$$\mathbb{P}(E_1) = \mathbb{P}(X = 0 | d_e(X) = 0) = \frac{(1 - PFA(X))(1 - \gamma)}{(1 - PoD(X))\gamma + (1 - PFA(X))(1 - \gamma)} \quad (14)$$

$$\mathbb{P}(E_2) = \mathbb{P}(X = 0 | d_e(X) = 1) = \frac{PFA(X)(1 - \gamma)}{PoD(X)\gamma + PFA(X)(1 - \gamma)} \quad (15)$$

$$\mathbb{P}(E_3) = \mathbb{P}(X = 1 | d_e(X) = 0) = \frac{(1 - PoD(X))\gamma}{(1 - PoD(X))\gamma + (1 - PFA(X))(1 - \gamma)} \quad (16)$$

$$\mathbb{P}(E_4) = \mathbb{P}(X = 1 | d_e(X) = 1) = \frac{PoD(X)\gamma}{PoD(X)\gamma + PFA(X)(1 - \gamma)} \quad (17)$$

350 where γ is the probability of presence of a defect over the inspection section, i.e., $\gamma = \mathbb{P}(X = 1)$, so $(1 - \gamma) = 1 - \mathbb{P}(X =$
 351 $1) = \mathbb{P}(X = 0)$ is the probability of the absence of a defect.

Normally, the PoD is a monotonically increasing function that depends on the defect depth, which can be approximated “experimentally” using the ratio of the actual number of defects over the total number of reported defects in a defect depth range [5]. Different authors have reported this approach to describe the probability of indication in a given range of interest [32]. Consider a segmentation of the depth of the defects given by $d_i, i = 0, \dots, m$ where $d_m \leq \max(d_{ILI})$ being d_{ILI} the reported depths at the ILI measurement, whereas $d_0 = 0$ represents an intact pipeline. Accordingly, denote by n_i for $i = 1, \dots, m$ the number of defects correctly identified by the inspection tool, over a total of N_i , for each segment $[d_{i-1}, d_i]$, then the probability of true indication (PTI) can be estimated by $PTI \sim n_i/N_i$ [32]. The problem of this approach for PoD without a field validation is that the defect’s existence is assumed but cannot be guaranteed.

On the contrary, consider the event E_4 , which evaluates the probability that a defect exists given it was already detected. This event was used assuming detection in both inspections² it does exist. Note that this approach would estimate the real number of existent defects from the first inspection; however, this assumption would neglect those repaired defects, and it may include the unlikely case where a non-existent defect was reported in both inspections. Nonetheless, this is the best approximation based on the available information considering the lack of field sampling.

The obtained results are shown in Figure 15, including exponential and log-logistic fits based on the equations depicted in Eq. 18 and Eq. 19, once the defect depth is segmented using equidistant quantiles. Similar expressions have been implemented by other authors to estimate the PoD such as Park et al. [33], Baskaran et al. [34], or Yazdi et al. [35].

$$f_{exp}(d) = \gamma_d \left[1 - \exp\left(\frac{-d}{\lambda_d}\right) \right], \quad (18)$$

$$f_{Logl}(d) = \frac{\exp(\alpha_d + \beta_d \ln(d))}{1 + \exp(\alpha_d + \beta_d \ln(d))}. \quad (19)$$

These fittings were determined using the modified nonlinear least-squares function *nlsLM* of the package *minpack.lm* in R, which incorporates the Levenberg-Marquardt algorithm. The obtained coefficients, as well as their confidence intervals and standard error, are displayed in Table 7. Overall the exponential and log-logistic functions agree very well with the “experimental” data obtained from the depth of the matched defects from the first inspection. The probability reaches 1 near 30%t deep for the inner wall, which means that any defect deeper than 30%t already detected would guarantee its presence on the inner wall. Timashev & Bushinskaya also reported a similar percentage by establishing that the probability of detection of an ILI tool is almost one [32]. For the outer wall, a depth of 30%t achieves a lower probability of 0.8, partially explained by the amount of data at the outer wall and the overall more profound defects than those located at the inner wall.

Table 7: Fitted parameters for the exponential and log-logistic function applied on the $\mathbb{P}(E_4)$

| Parameters | Inner wall | | | | Outer wall | | | |
|-------------|-------------|---------------------|-------|-------|-------------|---------------------|-------|-------|
| | Coefficient | Confidence interval | | SE | Coefficient | Confidence interval | | SE |
| | | 2.5% | 97.5% | | | 2.5% | 97.5% | |
| λ_d | 0.836 | 0.623 | 1.180 | 0.172 | 0.838 | 0.5214 | 1.552 | 0.282 |
| γ_d | 1.115 | 0.966 | 1.365 | 0.085 | 0.887 | 0.7185 | 1.301 | 0.110 |
| α_d | 1.320 | 1.211 | 1.438 | 0.050 | 0.541 | 0.4384 | 0.648 | 0.049 |
| β_d | 2.272 | 1.896 | 2.667 | 0.171 | 1.011 | 0.6545 | 1.385 | 0.167 |

Following a similar procedure, the probability of event E_2 was determined, considering the defects that could not be matched, as the counting variable n_i . As it was remarked before, the definition of E_2 and E_4 follows that $\mathbb{P}(E_2) = 1 - \mathbb{P}(E_4)$, so additional functions were not necessary, and the “experimental” results were compared with the complement of the functions obtained from Table 7 (see Figure 16). The results show a good agreement between the fitted functions and the data of the unmatched defects, although this result could be expected using the definition of the raw probability of no matches, i.e., the complement from each depth segment.

²Initially detected in the first inspection and latter matched with another defect from the second inspection.

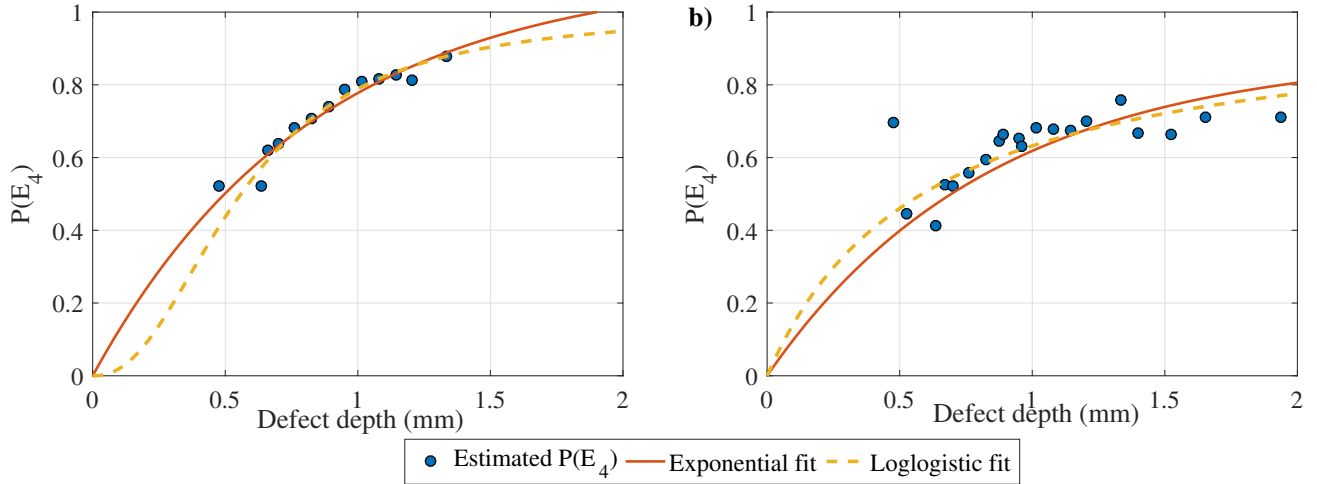


Figure 15: Estimated $\mathbb{P}(E_4)$ with the exponential and log-logistic fits for the a) inner and b) outer wall matched records in ILI1.

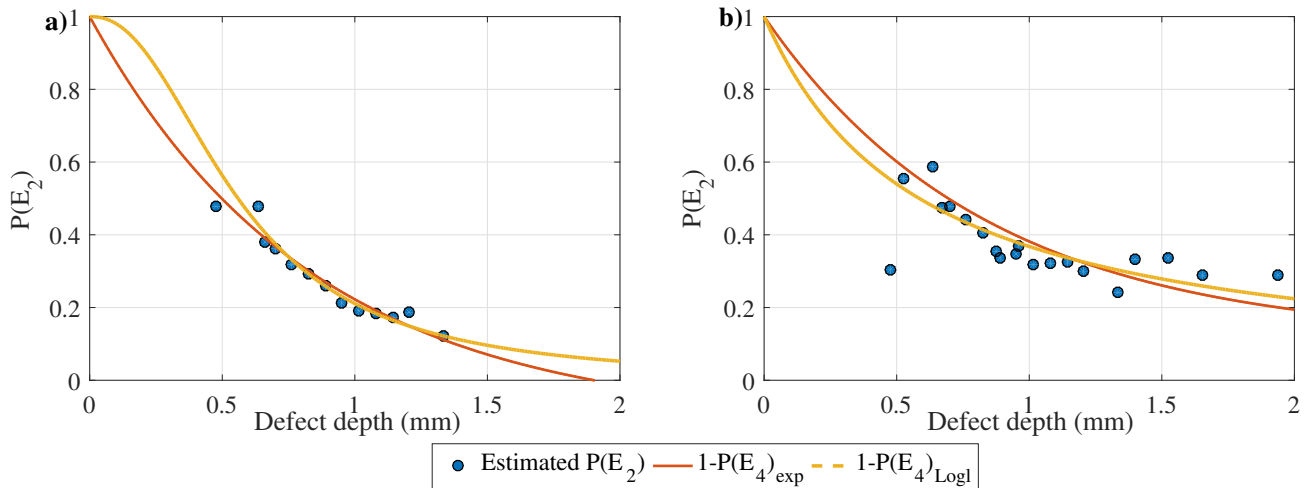


Figure 16: Estimated $\mathbb{P}(E_2)$ with the exponential and log-logistic $\mathbb{P}(E_2)$ complement fits for the a) inner and b) outer wall.

381 Nevertheless, this pattern is obtained regardless of the data used to fit $\mathbb{P}(E_4)$ and to calculate $\mathbb{P}(E_2)$. To demonstrate
 382 this pattern, consider a cross-validation approach using 70% of the data as a training set to determine the exponential
 383 and log-logistic fits for $\mathbb{P}(E_4)$, and the remaining 30% to estimate $\mathbb{P}(E_2)$ (test set). This procedure was implemented
 384 100 times using random sampling, and the Mean Standard Error (MSE) from the $1 - \mathbb{P}(E_4)$ predictions and the
 385 estimates of $\mathbb{P}(E_2)$ were determined. The results shown in Figure 17 indicate that these probabilities fit quite well by
 386 obtaining an average MSE of 0.002 and 0.007 for the inner and outer wall, respectively, which confirms the results
 387 obtained in Figure 16.

Although a complete PoD description is unknown, it is commonly assumed to behave as in Eq. 18 and Eq. 19
 with exponential or log-logistic fits [26, 36, 37]. Inspection vendors usually provide a reference PoD for depths from
 10 to 15%t of 0.90, commonly used to fit these theoretical probabilities. For instance, Zhang & Zhou implemented
 the exponential version (Eq. 18) with $\gamma_d = 1$ and $q = 1/\lambda_d$, where q represents a detection capability inherent from
 the inspection tool. The objective is to avoid this theoretical PoD but take advantage of the probabilities of E_4 or E_2
 to estimate the PoD. Recall from Eq. 17 that $\mathbb{P}(E_4)$ depends on the probability of detection, false alarm, and defect
 existence (γ). From these probabilities, inspection vendors commonly report a PoD reference point, whereas PFA is

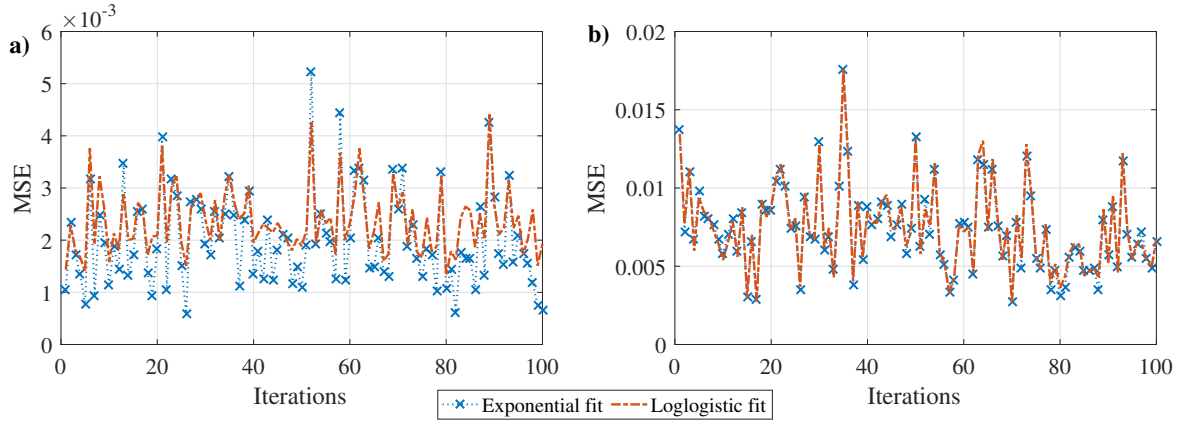


Figure 17: Mean Standard Error of $\mathbb{P}(E_2)$ and the $1 - \mathbb{P}(E_4)$ predictions under a cross-validation approach.

known to be independent and constant for the defect size [5]. Therefore, if γ is estimated, and the reference point is used, an estimate of the probability of false alarm can be solved using Eq. 17. Following Timashev & Bushinskaya, the probability of true detection and thus the existence of a defect would be at most [32]:

$$\gamma = \frac{A_d}{A_p}$$

388 where A_d is the surface area occupied by all the existing defects, and A_p is the total surface area being inspected. These
 389 surface areas would not contemplate the depth of the defects, and they depend on the inner and outer diameters³ for
 390 the inner and outer walls, respectively. The existing defects were again assumed to appear in both inspections, but this
 391 probability could be higher by including additional defects. Regarding the PoD, a reference point of $PoD(15\%t) =$
 392 0.90 was chosen based on the information reported by the inspection vendor for different MFL inspection tools.

393 Based on the mentioned above, the detection capabilities in each inspection, the probability of existence, and the
 394 probability of false alarm were determined for both pipe walls (Table 8). The results indicate that γ for the inner wall
 395 is about five times the probability for the outer wall, which is consistent with the number of defects and the obtained
 396 matches. However, the difference is shorter between the two obtained PFA. These false alarm probabilities are not far
 away from those reported by other approaches [38, 39]; however, they are specific for the inspection tool.

Table 8: Detection and existence summary results

| Pipe wall | Detection Capability (q) | γ | PFA |
|-----------|------------------------------|----------|--------|
| Inner | 2.42 | 0.2655 | 0.0971 |
| Outer | 2.42 | 0.0503 | 0.0291 |

397 Finally, based on the results in Table 8, the probability of detection (PoD) was estimated using the PFA, γ , and the
 398 $\mathbb{P}(E_4)$ from both pipe walls. For this purpose, each “experimental” point from Figure 15 were contemplated to solve
 399 again Eq. 17. The results are depicted in Figure 18 with green dots. This figure also includes a log-logistic fit and the
 400 expected theoretical function using the exponential fit with the detection capability. Note that the expected PoD has
 401 a clear difference with the log-logistic fit, but this difference is almost diminished after a PoD of 0.9, considering the
 402 procedure to determine both false alarm probabilities. The estimated PoD would be more conservative considering a
 403 lower detection probability that requires further tests and field validations.
 404

405 This figure demonstrates that determining the probability of detection might not be straightforward; the proposed
 406 approach seeks to provide insights about PoD and PFA based on the data from consecutive inspections. Although the

³The inner diameter is given by $D_i = D - 2t_i$, where D is the outer diameter, and t is the wall thickness at the i^{th} location.

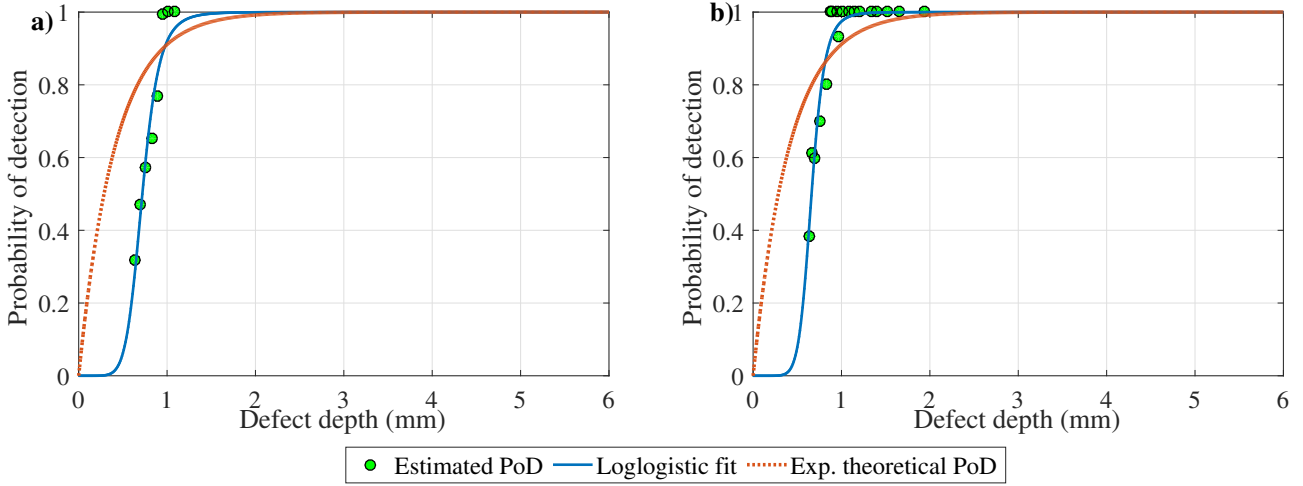


Figure 18: Estimated Probability of Detection with the complement log-logistic PoD fit and the theoretical exponential PoD for the a) inner and b) outer wall.

407 matching process may not identify all the existent defects in the pipeline, which could affect both $\mathbb{P}(E_4)$ and $\mathbb{P}(E_2)$,
 408 the obtained results are fair enough based on the available information. Figure 17 supports this result with the MSE
 409 outcomes under a cross-validation approach. The estimated PoD and PFA could support future intervention decisions
 410 considering whether a defect exists or not based on the defects detected by the ILI tool; for instance: 1) contemplating
 411 a predictive maintenance approach that dynamically adapts to imperfect repairs and replacements [40]; 2) quantifying
 412 how would be the economic gain by doing an inspection or a preventive maintenance [41]; and 3) predicting the
 413 distribution of corrosion defects' depth under adaptive time-dependent environmental conditions [42]. Besides, this
 414 information can be used to support reliability calculations under a noisy data context; for instance, considering a
 415 Gamma Process [43], multiple correlated defects [44], or evaluating a Spatio-temporal analysis that benefits from
 416 FEM simulations [45]. Further inspections and field validations would provide more realistic results, aiming to deal
 417 with the uncertainties inherited from the inspection tool, which, in turn, would seek to avoid unnecessary or costly
 418 repairs. Unfortunately, the inspection vendor did not provide the PoD and the PFA, but it would be interesting to
 419 compare how far they are from the predictions obtained with the matching process. Further estimates could also help
 420 to evaluate the consequence of the detection in terms of repair decisions, considering, for instance, the probability of
 421 good and wrong assessments [19, 46].

422 Non-destructive techniques are subjected to different types of randomness affecting the acceptance and rejection
 423 decisions of defects; PoD gives a path to evaluate the pipeline's condition, including these uncertainties. Field valida-
 424 tions would not only allow evaluating conditional probabilities given a detection, but also the joint probabilities based
 425 on a correct detection and existence [32]:

- 426 • Probability of True Detection (PTD) $\mathbb{P}(d_e(X) = 1, X = 1)$;
- 427 • Probability of True Non-Detection (PTND) $\mathbb{P}(d_e(X) = 0, X = 0)$;
- 428 • Probability of False Non-Detection (PFND) $\mathbb{P}(d_e(X) = 0, X = 1)$; and
- 429 • Probability of False Detection (PFD) $\mathbb{P}(d_e(X) = 1, X = 0)$.

430 According to Timashev & Bushinskaya, these probabilities can be interpreted from a geometrical perspective by
 431 considering the area occupied by each case after a field validation [32]. Consider a pipeline segment with a length
 432 of L and diameter D , and let Figure 19 represent the output after the field validation. Consider that the black spots
 433 correspond to the defects that exist and were detected; the contoured spots with dash lines were defects not detected,
 434 but they do exist, and the light spots with continuous lines were non-existing defects reported by the inspection tool.
 435 Finally, the remaining area corresponds with an intact pipeline that was correctly not reported any defect by the
 436 inspection tool. Timashev & Bushinskaya acknowledged these probabilities by considering upper limits based on the

437 total area occupied and considering that $PTD + PTND + PFND + PFD = 1$, which is different from the pairs of
 438 events (E_2, E_4) and (E_1, E_3) based on the conditional definition.

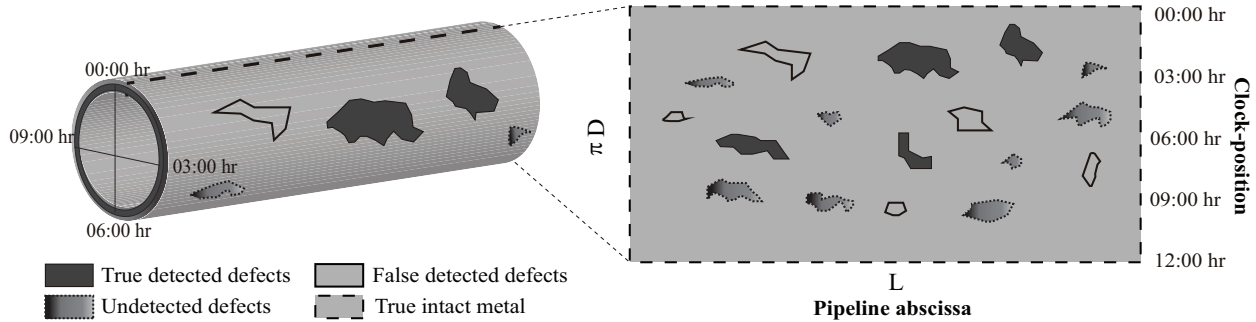


Figure 19: Scheme of a corroded pipeline condition with detected and existence results. Adapted from Timashev & Bushinskaya [32].

439 8. Conclusions

440 Pipeline integrity evaluation requires monitoring the evolution of the corrosion attack in time. Location and
 441 detection uncertainties in ILI measurements complicate this task, so a matching approach is essential. This work
 442 proposed a new approach using a Voronoi partition to filter initial possible matches, which is later implemented under
 443 an iterative approach with closed-forms “best” affine transformations and a correspondence matrix and outlier vectors
 444 optimization approach. Although pipeline operators may have more than two ILI measurements, which are helpful for
 445 corrosion growth monitoring and modeling, the proposed approach is recommended for two consecutive inspections.
 446 ILI measurements are implemented every 2 to 6 years, making the pipeline prone to maintenance or replacement
 447 procedures. This sequential approach could help follow the corrosion evolution more efficiently.

448 The main findings are summarized below:

- 449 1. The proposed approach focused on a transformation that contemplates the uncertain location of a corrosion
 450 defect in any direction by considering a nearest-neighbor perspective. This approach helps get competitive
 451 results than a traditional point matching problem with a defined affine transformation like the temperature
 452 annealing method.
- 453 2. Based on a segment of a real case study, this paper illustrated how the approach could identify 11 out of 21
 454 possible matches. Based on the proposed matching, about 50% of the data could be matched between two
 455 inspections, obtaining a final number of matches of 14314 for the inner wall and 1714 for the outer.
- 456 3. The synthetic results indicated a true matching ratio for the proposed approach of 0.848 against 0.607 for the
 457 annealing case, after a sensibility analysis of their parameters. This matching ratio was also compared with an
 458 AMPL solver KNITRO in the NEOS server, obtaining similar (and even better) results. These results highlight
 459 the proposed approach as an interesting alternative for pipeline engineers that monitor the evolution of corrosion
 460 degradation.
- 461 4. Some insights about the probability of detection (PoD) and false alarm (PFA) were obtained based on the
 462 classification of *new* and *old* defects. For this purpose, the probabilities of the presence or absence of a defect
 463 given its detection from Rouhan & Schoefs [5] were implemented from an “experimental” point of view with
 464 recognized exponential and log-logistic fitting functions. The results allow us to estimate the PoD and PFA
 465 based on the reported data, which, in turn, can be implemented for further reliability analysis of the pipeline.

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