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RELIABILITY BASED PREVENTIVE MAINTENANCE FOR CORRODED PIPELINES

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Abstract. Pipeline's infrastructure grows every year, worldwide. Although pipelines are one of the safest ways of transporting oil and gas, corrosion is a major concern in the petroleum industry. Due to corrosive environment (underground or undersea), defects can be generated and increased through time, reducing pipe's resistance. In order to evaluate effectively pipeline's integrity during its service life, understanding uncertainties involved in corrosion is necessary; therefore, reliability assessment is necessary. With reliability predictions, maintenances plans can be developed. Maintenance means that a segment of pipe is excavated and the corrosion defects are "fixed", which restores the pipeline segment to its pristine condition, without defects. Whenever reliability coefficient falls to a predefined threshold, maintenance takes place, this approach is called Reliability Based Preventive Maintenance (RBPM), and it is used in this paper, according to industry's practice. There are two main contributions in this paper: first, a parametric study is conducted, using RBPM strategy, and the parameters are 3 design variables: wall thickness of the pipe, type of steel used (tensile strength) and also operation (internal) pressure, which is the load considered in all examples. In addition to that, the second contribution is to evaluate how different ways of modeling growth of defects influence maintenance planning; preliminary results indicate that the way of modeling growth can cause significant changes in the reliability coefficient against time. The parameters will be considered as random variables, with distributions, means and standard deviations considered as indicated in literature. The internal pressure will be considered as a stochastic process.

Keywords: Corroded pipelines. Reliability. RBPM. Maintenance.

1 Introduction

Pipelines are a safe way of transporting petroleum derivatives, such as natural gas and oil. Tee and Pesinis [1] indicate that pipeline's infrastructure grows around 3-4% globally, every year. On the other hand, the same authors also show that the majority of pipes are operating for at least 20 years. The aging of pipelines can bring different problems, such as corrosion; during its lifecycle, defects (regions where the wall thickness of the pipe is reduced) can be generated and grow. According to Gong and Zhou [2], corrosion was responsible for 35% of the failures in pipelines in Canada, between 2010 and 2014; the authors also present a similar number (32%) for United States, between years 2002 and 2013.

Therefore, it is important to analyze the pipe's behavior during its lifecycle, in order to guarantee a proper integrity management; many authors, such as Ossai, Boswell and Davies [3] indicate that a reliability analysis is essential in this matter, because there is a lot of uncertainties in corrosion generation, growth and measurement. Gong and Zhou [2] explain that these uncertainties can be related to: pipe's geometry (wall thickness, for example), defects size, materials (tensile strength), ad others, like measurements (during inspections) and model of analysis.

In this context, one of the main contributions of reliability analysis is the development of integrity management strategies. With the behavior of reliability against time, decisions can be made, during the lifecycle; for example, if reliability coefficient reaches a low value, the operation (internal) can be reduced; in addition, maintenances can be made: in order to make repairs in the defects, the pipe is excavated and restored to its pristine condition, without the defects; this procedure improves significantly reliability. This strategy, in where preventive maintenances take place depending on the reliability coefficient, is a well-established practice in industry, and it is called Reliability Based Preventive Maintenance (RBPM). Studying this strategy is one the main objectives of this paper.

Although RBPM strategy is not new in literature, this paper presents a different study considering this methodology. First, it is conducted a parametric study, related to 3 design variables: pipe's wall thickness, tensile strength (material) and internal pressure, which is the only load considered. There are several studies in the matter of maintenance planning, but there are few related to parametric study on design variables. Tee and Pesinis [1], for example, presented parametric analysis, but the parameters studied were related to the stochastical processes involved in modeling generation of new defects and variation of internal pressure.

Besides that, another important contribution of this work is to analyze different corrosion growth models; it is not common in literature to discuss the influence of the growth model adopted. Tee and Pesinis [1] used a well-established empirical model, while Zhang and Zou [4] used gamma process, and Ossai, Boswell and Davies [3] utilized markovian processes. As long as there are many different models to evaluate growth of defects, it is investigated their influence in RBPM strategy; to both cases (parametric studies on design variables and consideration of different growth models), the results are presented as a maintenance plan, which means the expected number of maintenances and their time to take place, during the lifecycle.

In order to achieve that main objectives, this paper is organized in 5 sections. This introduction is section 1, and presents a general overview of the discussion of the paper; in section 2, models for generation (1 model) and growth of defects (2 models) are presented and discussed. In addition, section 3 introduces the strategies related to maintenance, in special RBPM; section 4 contains the results, divided in: parametric study of design variables and discussion of influence of the growth model. Finally, section 5 summarizes the conclusions and discussions of the paper, and then the references are listed.

2 Corrosion's evolution in time and failure calculation

There are many ways of consider corrosion's evolution in corroded pipelines; this paper used some simplifications, commonly adopted in literature:

- Corrosion defects are independent; it means that no interactions are considered, and the longitudinal position where a new defect takes place in the pipe does not influence the results. This is similar to what Tee and Pesinis [1] and Zhang and Zou [4] used in their papers;
- The generation of new defects was modelled by Non-Homogeneous Poisson Process (NHPP), described in section 2.1; this method was also used by Tee and Pesinis [1] and Zhang and Zou [4];
- The generated defects are defined by length and depth, and its growth is modelled by 2 different models: an empirical model, the same one employed by Tee and Pesinis [1], Gomes, Beck and Haukaas [5] and Bazán and Beck [6] and a linear one, which was also used by Bazán and Beck [6] and Gong and Zhou [2];
- In this paper, it is considered only one mode of failure: burst; so, the burst pressure, failure pressure, in this case, is calculated and compared to internal pressure; if the internal pressure is higher than failure pressure, so there is failure. The failure pressure is calculated through an empirical model: RPA, while internal pressure is defined by a Poisson Square Wave Process (PSWP); both methods were used by Tee and Pesinis [1].

2.1 Generation of new defects

During lifecycle, corrosion defects are generated in the pipeline. The model commonly employed in literature to describe this process is a Non-Homogeneous Poisson Process (NHPP), which can be calculated using equations from 1 to 3. This model calculates the number of defects generated during the lifecycle and their initiation times, that can be calculated using the procedure illustrated in figure 1; one main assumption is that the initiation times are not produced in a uniform manner in time.

In this way, equation 1 indicates the intensity factor to the pipe; λ_0 and b are both positive empirical constants, and their values should be adjusted on inspections data and industry's expertise. Tee and Pesinis [1] suggested the adopted values from table 1. As a matter of fact, these researchers presented a parametric study on λ_0, with the three values indicated in table 1; this paper used all three values, in order to compare the obtained results with the ones presented in Tee and Pesinis [1]. In addition, integrating equation 1 in time, if the superior limit is considered as the lifecyle or Time Horizon (T), it results in equation 2, which can be physically interpreted as the expected number of defects generated from time t=0 to generic time t. When t=T, there is the expected number of defects for the whole lifecycle. Besides that, the total number of defects generated in generic time t follows a Poisson distribution, such as indicated in equation 3, which describes the probability density function (PDF) for this Poisson distribution.

Table 1. NHPP model variables and values

Variable	Adopted value
λ_0	0.0064; 0.0128 e 0.0256
b	2

$$\lambda(\tau) = \lambda_0 \tau^b \tag{1}$$

$$\Lambda(T) = \int_0^T \lambda(\tau) d\tau \tag{2}$$

$$f_p = \frac{(\Lambda(t))^{N(t)} e^{-\Lambda(t)}}{N(t)!} (t > 0) \tag{3}$$

With the number of defects in a period of time t, it is also necessary to define when each defect takes place. Zhang and Zou [4] describe a procedure to do that (figure 1). Steps 1 and 2 are, basically, using equations 2 and 3, respectively. After that, there is a loop, and the initiation is determined for each defect separated (step 3); steps 4 and 5 are random generations of numbers, between 0 and t (called "T0") and 0 and 1 (called "u"), respectively. In step 6, the random generated time is applied in equation 2, and this result is divided by the one in step 1. If this ratio is less than "u", than the time "T0" is the initiation time for that defect; if not, then the process is repeated, until a valid "T0" is found. This loop is repeated for the number of defects found in equation 2.

Step 1: Calculate the expected number of defects Λ(t=T), using equation 2;

Step 2: Estimate the total number of defects N(t=T), using PDF from equation 3;

Step 3: Set i=1.

WHILE $\left[\, i < N(T) \,\right]$

Step 4: Random generation of number "u", between 0 and 1: $0 \le u \le 1$;

Step 5: Random generation of "candidate time" "T_0", between 0 and T: $0 \le T_0 \le T$;

Step 6: Calculate the expected number of defects for the candidate time $\Lambda(t=T_0)$, using equation 2;

IF $\left[\; u < \frac{\Lambda(T_0)}{\Lambda(T)} \;\right]$

Step 7: set $t_0(i) = T_0$ and i=i+1, which means T_0 is the initiation time for the *i*th defect;

ELSE

Step 8: Repeat steps 4,5,6, until the "if" condition is satisfied

END (IF)

END (WHILE)

Figure 1. Procedure for calculation of initiation times of new defects.

2.2 Growth of defects

There are many different ways to consider the growth of defects in pipelines; Bazán and Beck [6] conducted a study, explaining 4 different categories of methods: linear random, linear stochastical, nonlinear random and nonlinear stochastical. In this paper, 2 different methods are presented and compared in section 4: one linear random, based on Bazán and Beck [6] and one nonlinear random, based on Tee and Pesinis [1].

In the linear random model, the depth and length of defects grows in time, according to equations 4 and 5, respectively; in which d_0 is the initial depth, while R_d is the correspondent corrosion growth rates and "t" is the desired time. These 4 variables are random distributed, and table 2 indicates their distributions and parameters (Bazán and Beck [6]). The coefficients of variation are defined as COV in this paper.

$$d(t) = d_0 + R_d t \tag{4}$$

Table 2. Linear model variables and values

Variable	Probability distribution	Parameters
R_d	Gamma	mean μ=0.082 mm/y; COV=65%
d_0	Normal	mean μ=2.64 mm; COV=31%

Although the linear random is easier to calculate and use, it is well established in literature that it is conservative (Bazán and Beck [6]). Therefore, other less conservative approaches were also developed, such as this empirical power law model, which is nonlinear and random. This model is used by many authors, such as Tee and Pesinis [1], and it basically corresponds to equation 6, in where κ and α are empirically determined parameters, that depend on soil properties; their values are on table 3, in which "t" is the desired time and t_0 is the initiation time for the respective defect.

$$d(t) = \kappa (t - t_0)^{\alpha} \tag{5}$$

Table 3. Empirical growth model variables and values

Variable	Probability distribution	Parameters
κ	T-Location scale	mean μ=0.168 mm/y; scale σ=0.063 and shape ν=4.780
α	Inverse Gaussian	mean μ=0.762 and shape λ=27.016

2.3 Internal pressure

It is consistent to industry practice to assume that internal pressure fluctuates randomly in time; Tee and Pesinis [1] use a Poisson Square Wave Model (PSWP) to model this variation. Figure 2 indicates the behavior of PSWP: there are randomic pulses (intervals between times), and in each pulse, pressure assumes a constant value. The duration of the pulse is determined by equation 6: a randomic number "u" is generated (between 0 and 1), and then used in the equation. λ is a deterministic parameter from the model, and Tee and Pesinis [1] present, in their paper, a parametric study on such parameter. They have studied 3 different values, and concluded it does not have a major impact on failure pressure and reliability. Therefore, it was chosen the value 1.0, as indicated in table 4.

Besides duration of each pulse, the model also requires the value of pressure in each interval; this value, called “P”, follows a Gumbel distribution, as described in table 4.

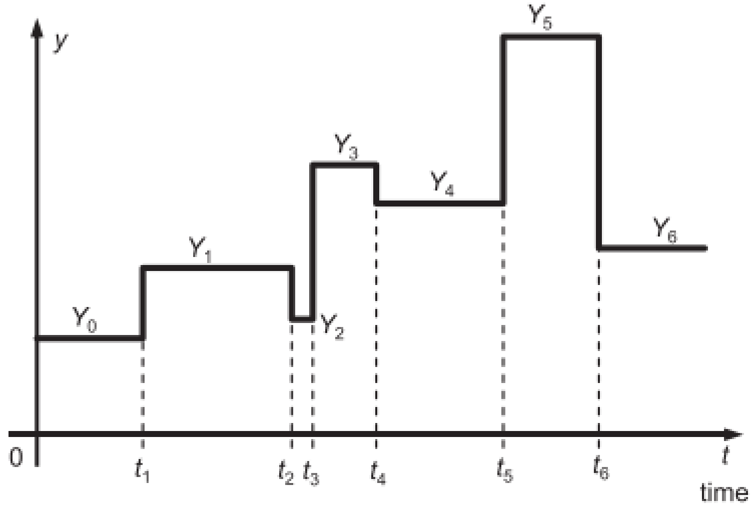

Figure 2. PSWP for internal pressure (adapted from Bazán and Beck [6]).

$$dt = (-\lambda)^{-1}\ln(u) \tag{6}$$

Table 4. PSWP for internal pressure: variables and values

Variable	Probability distribution	Parameters
λ	Deterministic	1.0
P	Gumbel	mean μ=10.857 and COV=2%

2.4 Failure pressure calculation model

There are many different ways of calculating failure pressure: experimental research, numerical modelling (using finite element analysis) and empirical methodologies. According to literature, when it comes to reliability analysis, like the focus of this paper, it is more common the use of an empirical method for estimating failure pressure, in order to reduce the computational cost involved in the many repetitions of stochastical analysis. Zhang and Zou [4] uses a B31 modified model, while Liu et al [7], Bazán and Beck [6] and Gong and Zhou [3] utilized variations of another model: PCORRC. Tee and Pesinis [1], on the other hand, used a different model: RPA. As long as this paper used these authors result to validate the maintenance strategy, RPA is also used in this work. This empirical is model is described by equations 7 and 8; the random variables are described in table 5, such as indicated by Tee and Pesinis [1].

$$r_b = (\sigma_y + 69)\frac{2wt}{D}\left[\frac{1 - a\frac{d}{wt}}{1 - a\frac{d}{Mwt}}\right] \tag{7}$$

Where:

- r_b is burst capacity (or failure pressure), in MPa;
- σ_y is the yield stress, in MPa, depends on the type of steel used;
- wt is the wall thickness of the pipe, in mm;
- D is the outside diameter of the pipe, in mm;
- d is corrosion defect depth, in mm;
- L is corrosion defect length, in mm;

"M" and "a" are factors, calculated according equation 8; it is important to point out that depending on defect length (L), there are 2 different manners of calculating M and a.

$$M = \begin{cases} \left[1+\frac{0.6275L^2}{Dwt}-0.003375\left(\frac{L^2}{Dwt}\right)^2\right]^{\frac{1}{2}} \text{ and } a=0.85, \text{ if } L<\sqrt{20Dwt} \\ 2.1+0.7\frac{L^2}{Dwt} \text{ and } a=1-0.15\frac{64.10^6}{\left(\frac{L^2}{Dwt}\right)^6}, \quad \text{if } L\geq\sqrt{20Dwt} \end{cases} \tag{8}$$

Table 5. Empirical growth model variables and values

Variable	Probability distribution	Parameters
σ_y	Normal	mean μ=594 MPa; COV=3%
wt	Normal	mean μ=8.96 mm; COV=1.5%
L	Lognormal	mean μ=105 mm; COV=130%
D	Deterministic	762mm

2.5 Reliability analysis

In order to conduct the reliability analysis, the models presented in previous sections are combined with a Monte Carlo approach. At first, the lifecycle (Tf) is defined; after that, there is a generation of new defects and initiation times, from time t=0 to t=Tf. The time increment is defined as dt=0.125 years, according to Tee and Pesinis [1] and Gomes, Beck and Haukaas [5] used; for each new time, there are N generations of the random values presented in previous sections, the growth model from section 2.2 is applied, and then each defect is defined by its length and depth.

Therefore, it is possible to evaluate internal pressure for each time, using the method in section 2.3, and burst pressure for each defect in each time, using the model from section 2.4. So, for each time it is possible to determine the estimated number of failures (when internal pressure is bigger than burst pressure), and the division of this number for the total number of randomic generations (N) is an estimated probability of failure for each defect in the specific time.

Although this described methodology involves randomic generations of parameters, the number of defects and initiation times is also stochastical process; consequently, it means that each generation of new defects can lead to different results of probability of failure and realiability. In order to reduce that possible error, Tee and Pesinis [1] suggest that the above described methodology is repeated "m" different times, where each different generation is a new application of NHPP, with different numbers of defects and initiation times; by the end of computations, the reliability values in time is a media of the obtained values in all “m” new generations. This whole process is described in figure 3.

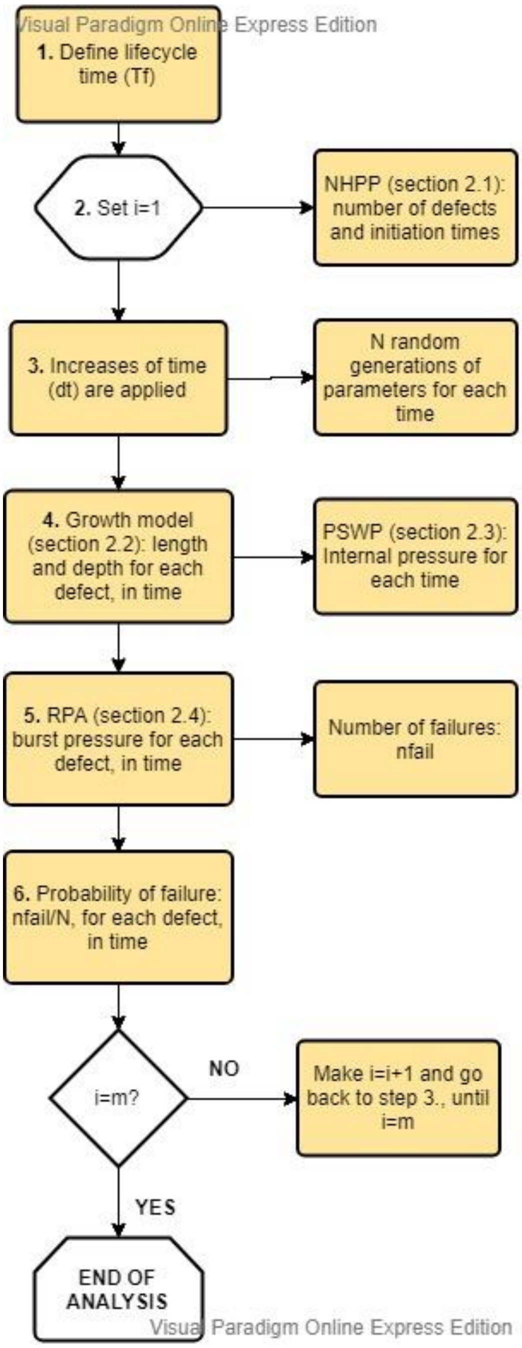

Figure 3. General view of reliability analysis applied in this work.

Equations 9 to 11 describe the process of calculating the failure probabilities (PoF); equation 9 shows the calculation of conditional probability of failure, which is calculated using failure probabilities from the the current time step and the next time step, for each “i” defect. In addition, equation 10 indicates how each individual probability of each defect is gathered, in order to obtain a probability for the group of defects. Finally, equation 11 presents the concept of the “m” generations; for each generation of new defects (and correspondent initiation times) there is a different probability, and the mean value of “m” generations represents the resultant probability.

$$PoF_i^{cond}(t_{j,}t_{j+1}) = \frac{PoF_i(t_{j+1}) - PoF_i(t_j)}{1 - PoF_i(t_j)} \tag{9}$$

$$PoF(t_{j,}t_{j+1}) = 1 - \prod [1 - PoF_i^{cond}(t_j, t_{j+1})] \tag{10}$$

$$PoF(t_{j,}t_{j+1}) = \frac{\sum_m PoF(t_{j,}t_{j+1})}{m} \tag{11}$$

3 Maintenance planning in corroded pipelines

3.1 Maintenance, inspections and repairs

Maintenance planning in corroded pipelines is essential in risk management (Liu et al [7]); whenever risks (measured by reliability) fall to unacceptable values, inspection and maintenance should be implemented, in order to reduce failure likelihood and consequences. For a buried pipeline, maintenance means excavating and recoating the defects; according to industry practice (Tee and Pesinis [1]), this kind of repair restores the burst capacity to the one of a new segment (without defects). In other words, the pipe returns to its pristine condition.

In addition, Gomes, Beck and Haukaas [5] and Liu et al [7], for example, indicate different categories of maintenance in their work: inspections and repairs. When an inspection takes place, it does not necessarily mean that a repair will be made; Gomes, Beck and Haukaas [5] presents one common criteria, in equations 12 and 13. If at least one of these criteria is satisfied, then a repair takes place, restoring the segment to its pristine condition. The same authors show that repairs also occur whenever failure happens.

$$d_{máx}(t) \geq 0.5wt \tag{12}$$

Where:

- $d_{máx}(t)$ is the maximum depth of the defect, in mm;
- wt is the wall thickness of the pipe, in mm;

$$1.39\,p(t) \geq r_b(t) \tag{13}$$

Where:

- $r_b(t)$ is burst capacity (or failure pressure) in time “t”, in MPa;
- p(t) is internal pressure in time “t”, in MPa.

In this way, industrial practice indicates that the chance of a repair event be not effective or be of poor quality is very low, and can be assumed to be 0 (Tee and Pesinis [1]). When it comes to frequency of inspections and repairs, there are 2 different approaches. These maintenance events can happen at fixed periods of time, and it is called Time-Based Preventive Maintenance (TBPM); however, preventive maintenances can also be based on reliability analysis, and happen every time that the reliability coefficient falls to a predefined threshold value. This later is called Reliability-Based Preventive Maintenance (RBPM) strategy. RBPM planning gives essentially the number of necessary maintenances, and the times when they should happen, considering the whole lifecycle of the pipeline.

3.2 RBPM strategy

Although industry more commonly adopts TBPM approach to linear assets (such as pipe systems), RBPM strategy has been widely applied and discussed in literature; Tee and Pesinis [1] performed a study, in which this paper is based, in where they investigated RBPM planning for different pipeline's system configuration. Their system was made of 3 serially connected segments, and they developed parametric studies on the modelling parameters, such as λ_0, from NHPP (section 2.1) and λ, from PSWP (section 2.3) and the reliability threshold (R_{THR}), which is the minimum reliability that indicates the need of a preventive maintenance.

Among other conclusions, these authors pointed out that λ_0 has a strong effect on RBPM planning, because the variation of this parameter changes significatively the times when maintenances should take place. For λ_0 = 0.0256, there are more defects generated, according to NHPP model, so that the first PM action should happen few years before the λ_0 = 0.0064 case, for example.

However, the parameter λ has little impact on the planning, because it almost does not change the schedule of PM actions; on the other hand, the threshold R_{THR} has the major impact on the planning, because it changes the number of PM actions needed to keep the pipeline system in a "safe zone". The bigger the value of R_{THR}, more PM actions are necessary, and these actions should happen sooner, in order to maintain the security levels defined by R_{THR}. From R_{THR}= 0.9 to R_{THR}= 0.95, there is a major changing: the number of maintenances needed grows from 6 to 9, considering the same lifecycle; but when compared to R_{THR}= 0.975, the number of actions does not grow, neither their schedule.

In order to obtain the RBPM planning results, Tee and Pesinis [1] explained their methodology; with the methods and models from section 2, it is possible to calculate reliability (R) for each segment separated, and the product of these individual reliabilities results on the system reliability, since they are serially connected. However, these obtained values are without the consideration of maintenance actions. To consider maintenances impacts, some assumptions must be made:

- A system contains "M" segments, and "m" ($m \le M$) vulnerable segments, which are repaired in PM actions; these segments are serially connected and are numbered according to the sequence of receiving PM;
- The failures of repaired and unrepaired segments are totally independent from each other; in practice, it means that the unrepaired subsystem does not affect the reliability of repaired segments;
- Repair times (duration) are ignored (considered to be null).

Therefore, a new reliability approach between PM actions is necessary, to describe the behavior of the system and the need of new maintenances during the lifecycle. When a segment receives a preventive repair, it is restored to its pristine condition; in terms of reliability, it is just like the reliability is the same as the unrepaired situation, but with time starting from 0. Considering "t" as the regular time, that increases from 0 to lifecycle, and the time when a segment is repaired is $T_{LPM,i}$. , t is only the difference between "t" and $T_{LPM,i}$., and indicates the new time referential. The conditional reliability is the multiplication of individual reliabilities of each pipe segments, calculated as indicated in section 2.5.

$$R_i(\tau) = R_i(t - T_{LPM,i}) \tag{14}$$

$$R_{sc}(t) = \prod_{i=1}^{M} R_i(\tau_i) \tag{15}$$

4 Case study

4.1 Validation of the methodology

In order to validate the previously described methodology, simulations have been made, according to what was described in sections 2 and 3; the parameters used were the same as in Tee and Pesinis [1]. First, it was conducted a parameter analysis on λ_0, which is the fundamental variable in the NHPP model for stochastical generation of defects (section 2.1). Table 6 indicates Tee and Pesinis [1] results, which will be considered as the reference. Using the methodology described in this paper, the results were obtained such as indicated in table 7.

Table 6. Results obtained by Tee and Pesinis [1].

λ_0	Maintenance schedule (years)
0.0064	42, 45, 50, 87, 90, 98
0.0128	37, 39, 43, 76, 80, 86
0.0256	33, 35, 39, 66, 71, 79

Table 7. Results obtained by the presented methodology, using methods such as Tee and Pesinis [1].

λ_0	Maintenance schedule (years)	Comparative deviation (%)
0.0064	42, 48, 53, 89, 95	0, 7, 6, 2, 6
0.0128	39, 41, 47, 81, 85, 94	5, 5, 9, 7, 6, 9
0.0256	35, 38, 41, 72, 76, 79	6, 9, 5, 9, 7, 0

In table 7, it is possible to observe, from the third column, the comparative deviation in percentage, considering the values from table 6 as the reference. The deviation varies between 0 to 9%, and is around 5% in most cases; these values indicate that the methodology in this paper does not reproduce entirely what was suggested by Tee and Pesinis [1], but there is a good agreement.

As long as the R_{THR} is a relatively low value (because it requires very high values for failure probability), in order to reduce computational effort and reduce time processing, the number of Monte Carlo samples was reduced from 10000 to 100, and then the same analysis were conducted again; the results are organized in table 8. By analyzing these results, it is possible to conclude that even with the reduction, the agreement was good.

In addition to that, to grasp an idea of dispersion of the approximations, it was conducted a comparative analysis between the different quantities of Monte Carlo's samples: for $\lambda_0 = 0.0064$, the simulation was repeated 20 different times, for 3 different quantities of Monte Carlo's samples: 10000, 1000 and 100. For the cases of 10000, 1000 and 100 samples, considering the time of the first maintenance, the obtained medias were, respectively, 43.5, 43.33 and 43.32 years; the standard deviations were, respectively, 0.68, 1.02 and 1.06. These results showed that the media in the 3 cases is less than 0.5% different, and it also indicated that standard deviations grow very little with the reduction of the number of samples, which indicates that the dispersion is low (considering a lifecycle of 100 years). This way, working with less samples in Monte Carlo analysis can be a good alternative to reduce processing time. Because of all that, all the other analysis in this paper were conducted with 100 samples in Monte Carlo's calculations.

Table 8. Results obtained by the presented methodology, with less Monte Carlo's samples.

λ_0	Maintenance schedule (years)	Comparative deviation (%)
0.0064	44, 45, 53, 90, 95	5, 0, 6, 3, 6
0.0128	37, 41, 46, 79, 85, 92	0, 5, 7, 4, 6, 7
0.0256	34, 37, 40, 70, 76, 80	3, 6, 3, 6, 7, 1

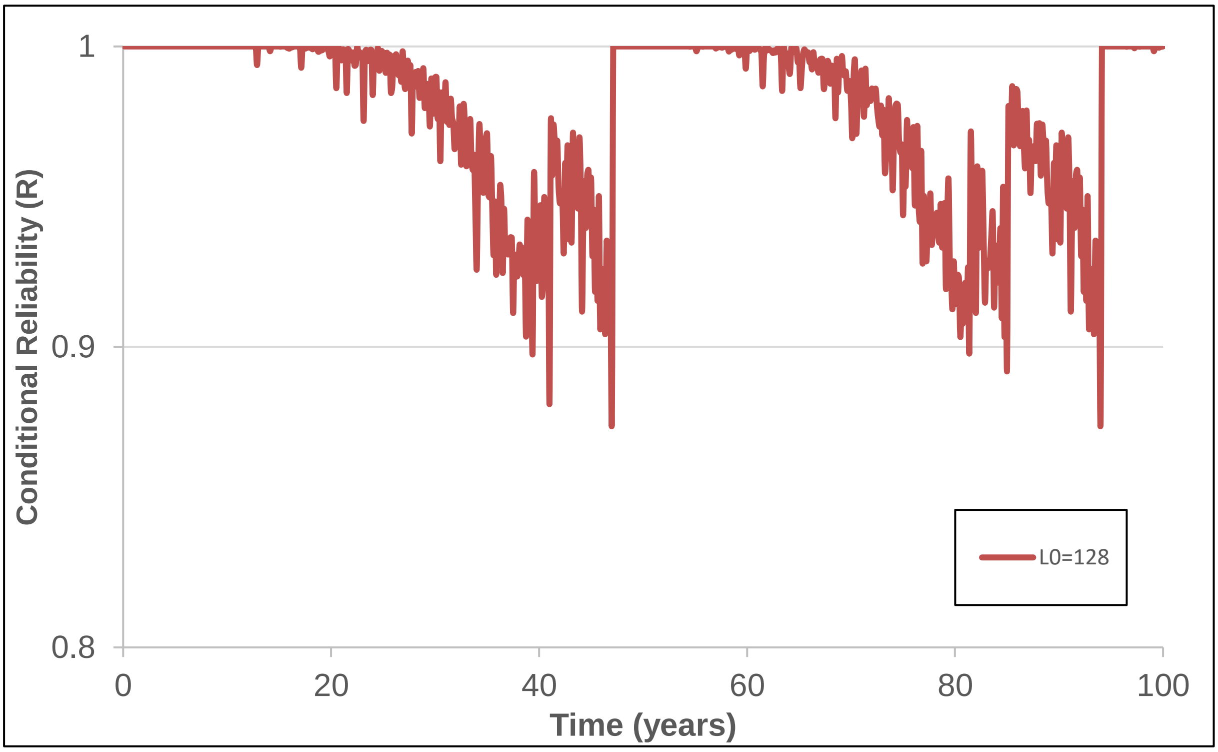

Figure 4. Conditional reliability x time for λ_0=0.0128 (table 7), using methodology of this paper.

In addition to that, figure 4 is a conditional reliability against time curve, for for λ_0=0.0128 (table 7). By analyzing this figure, it is possible to see the preventive maintenances (PMs) taking place in the exact times such as described in table 7. Besides, it is also possible to understand the essence of RBPM strategy: every time conditional reliability (R) falls to the R_{THR} value, a PM happens, and R grows. As long as the system from this paper contains 3 pipes, each PM is applied to a different one, and when the third PM happens it is possible to see in figure 4 that R goes back to its initial value: 1.

4.2 Parametric study on design variables

After the methodology's validation from the previous section, a new parametric study was made. Tee and Pesinis [1] have studied the influence of model's parameters λ_0 (from NHPP generation model) and λ (from PSWP internal pressure model). This paper, on the other hand, presents a different study, based on 3 important design variables: yield stress of the pipe's material (σ_y), wall thickness of the pipe (t) and internal pressure (P). All the analysis are performed considering N=100 samples for Monte Carlo's simulation and λ_0=0.0128; all the other variables are used such as indicated in section 2. This parametric study considers Tee and Pesinis [1] values as reference, and the changes in parameters are always compared to its respective reference values.

This new parametric analysis was conducted in order to investigate one different approach of RBPM strategy: the possibility of designing a pipe predicting its maintenance schedule, based on the risk level (defined by R_{THR}). In other words, it means that the pipe company can use the reliability analysis methodology described in this paper to estimate how many PM actions are necessary, during a pipeline's lifecycle, to keep the pipe below high-risk levels, or the reliability (R) is always bigger than the R_{THR}. Besides, some design parameters can be chosen depending on the maintenance schedule. As it is shown in this section, a bigger value of wall thickness (wt), for example, can lead to a lower number of PM actions, and it can take place in later times.

Here, the first parameter studied was yield stress (σ_y). Tee and Pesinis [1] used σ_y = 594 MPa (for an API 5L X80 steel). If a different steel is used (σ_y = 483 MPa), it is possible to observe that the number of PM actions increase; 2 more PMs are needed, during pipe's lifecycle. In addition, PM actions take place almost 10 years earlier. This reduction of 18.69 % in yield stress lead to a reduction of 21.62% in first maintenance time. Figure 5 shows the curve conditional reliability against time for the lower value of stress, and it is possible to compare it with figure 4 (which shows the results obtained by the reference), and it can be seen the increase in number of PM and at the same time the earlier need of PM. In reference, first maintenance should happen around year 37; in the scenario with reduced yield stress, 3 PMs should have already happened before year 37, as table 8 indicates.

On the other hand, increasing 9.42% in stress (σ_y = 650 MPa), leads to the same number of PM actions, but the first maintenance time increases 13.51%. Table 9 indicates the comparison between maintenance schedules of the discussed scenarios: lower yield stress value, reference value and higher value.

Table 9. Parametric study on the yield stress.

σ_y	Maintenance schedule	Number of PM actions
483	29, 31, 36, 57, 64, 71, 91, 98	8
594	37, 41, 46, 79, 85, 92	6
650	42, 44, 50, 87, 91	5

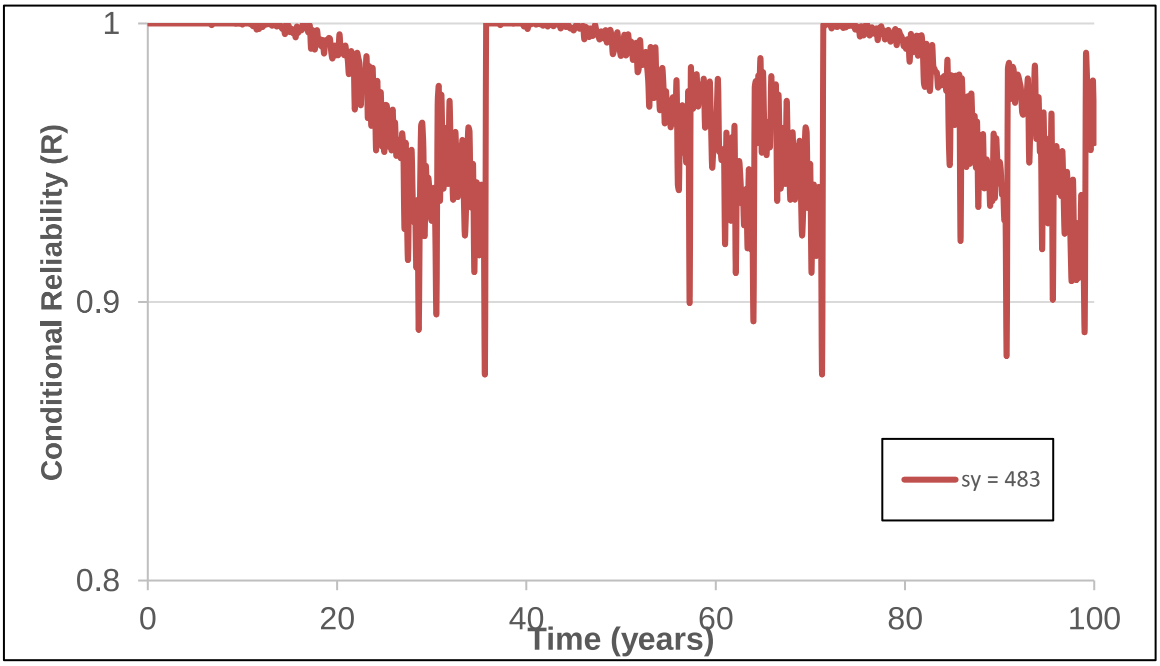

Figure 5. Conditional reliability x time for σ_y=483 (table 9), using methodology of this paper.

Next, the second parameter analyzed was wall thickness (wt) of the pipe. The reference value is wt = 8.96 mm, and it was studied a reduction of 11.55 % (leading to t = 7.925 mm) and an increase of 6% (leading to t = 9.5 mm). Table 10 shows the results; the reduction caused an increase of PM actions needed, a reduction of 18.91 % in first maintenance's time. By year 37, in reference model, the first maintenance should happen, while in the lower value of wall thickness situation 3 PMs have already happened. However, by increasing only 6%, it is possible to reduce one PM action.

Table 10. Parametric study on the wall thickness of the pipe.

wt	Maintenance schedule (years)	Number of PM actions
7.925	30, 31, 35, 62, 64, 71, 95, 98	8
8.96	37, 41, 46, 79, 85, 92	6
9.5	42, 46, 52, 88, 92	5

Finally, the third variable studied was the pipeline internal pressure. As long as it is described by a PSWP model, the change was made in the mean value: the reference is 10.857 MPa, just as indicated in table 4. Table 11 presents the comparison for the different pressures considered; as this table shows, a reduction of 11% (to P=9.653 MPa) leads to a small number of needed PM actions, and increases the times of the first maintenances in 5 years. By increasing the internal pressure 15% (to P=12.5 MPa), the quantity of PM actions remains the same, but these events need to take place earlier; the three first maintenances need to happen around 5 years before, when compared to the reference situation, but the three last are anticipated 15 years.

Table 11. Parametric study on the mean of internal pressure.

P	Maintenance schedule (years)	Number of PM actions
9.653	42, 46, 51, 88, 93	5
10.857	37, 41, 46, 79, 85, 92	6
12.5	32, 33, 39, 66, 70, 78	6

4.3 Results from different growth models

In section 2.2, two different growth models are presented: one linear random variable one, and the other a stochastical and empirical one. They are both applied to case study from Tee and Pesinis [1], and their comparison is presented in this section. Figure 6 indicates conditional reliability curves against time, and it is possible to understand that the linear model lead to a very conservative result, because the linear model leads to much more and earlier maintenances; table 12 shows the maintenance schedules for both models.

Table 12. Comparison between different growth models.

Growth model	Maintenance schedule (years)	Number of PM actions
Empirical	37, 41, 46, 79, 85, 92	5
Linear	23, 26, 29, 47, 52, 58, 75, 80, 87	9

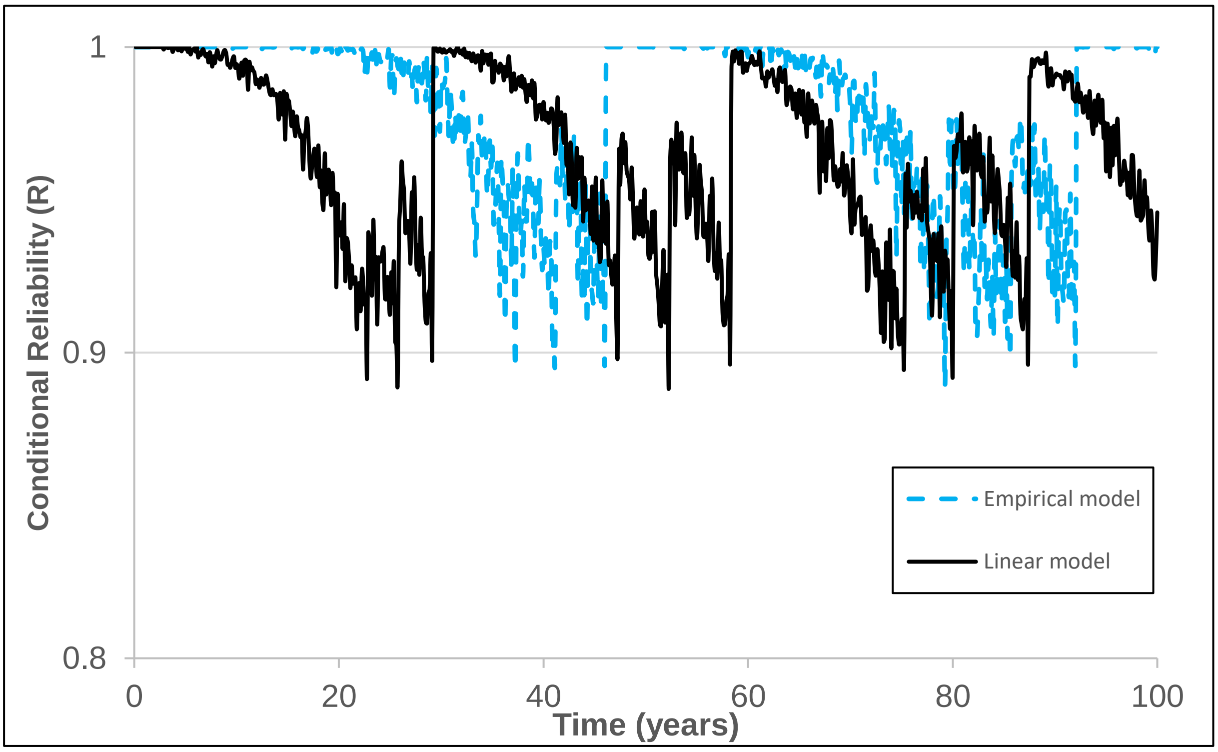

Figure 6. Conditional reliability x time for 2 different growth models: empirical x linear.

5 Conclusions

The main objective of this paper was to validate Tee and Pesinis [1] methodology for Reliability Based Preventive Maintenance (RBPM). After the initial "validation" of the method, additional contributions were made: a parametric study on design variables and a comparison between the results considering two different growth models. Considering all the results and methods explained and discussed in the paper, important conclusions can be drawn:

- Although there is a good agreement between this paper results and that presented by Tee and Pesinis [1], the comparative deviations between maintenance schedule indicates that it is possible to get even closer results;
- The parametric study on design variables suggested that reducing the wall thickness (t) has a major impact in the maintenance schedule than reducing the yield stress of the pipeline material;
- In addition, parametric analysis also showed that increasing internal pressure has a major impact in the last maintenances, anticipating them;
- Section 4.3 confirmed the importance of establishing a good agreement growth model; Choosing linear model leads to very conservative results: more and earlier PM actions, possibly not needed;
- RBPM strategy can be effectively used in the moment of pipeline's design as a tool for decision making; pipe's dimension, type of steel and mean of internal pressure can significantly influence in maintenance schedule.

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