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Availability-based reliability-centered maintenance planning for gas transmission pipelines

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ABSTRACT: A large portion of natural gas is transferred through transmission pipelines. For these facilities, in the United States, external corrosion has led to more than 1,700 failures in the past decades, causing a property damage of approximately $189M. Such numbers highlight the importance of maintaining such facilities in safe conditions to postpone corrosion failure. Given such criticality, addressing pipeline availability is of high importance from economic consequences perspective for a national economy. However, most of the developed methods merely rely on considering costs, reliability or condition levels as maintenance decision criteria and ignore the importance of continuity of operation and pipeline availability and. In this research, a maintenance planning framework is proposed for external corrosion of gas transmission pipelines through an availability-centered reliability-based maintenance planning procedure. This framework is based on pipeline reliability profile obtained from a Monte Carlo simulation. This simulation is carried on a previously developed failure prediction model for gas transmission pipelines buried in the Great Plains region of the US and considers failure uncertainties. In addition, a discrete event simulation (DES) approach is proposed to assess an availability-cost indicator of different maintenance scheduling alternatives for the case study of a 24-inch gas pipeline. This research reveals that a combination of wrap and replacement maintenance actions at the service life of 30.1 and 40.5 years respectively, is the most effective maintenance alternative in terms of improvement of availability per unit cost in the presented case study. This framework can help pipeline professionals in maintaining such facilities by considering their criticality using an availability-based maintenance scheduling approach. Such method can complement the conventional cost-based industry practices.

Keywords: pipeline, gas, transmission, preventive maintenance, planning, availability, cost, external corrosion, reliability, mean time to failure, mean time to repair.

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1. Introduction

Transmission pipelines are considered as a crucial portion of gas pipelines, passing through jurisdictions and international boundaries. Only in the United States, since 1996, more than 10,000 failures have been reported for gas transmission pipelines [1]. As a time-dependent failure source, corrosion is reported as the most frequent one, accounting for more than a quarter of the total reported failures. Such failures have led to a property damage of approximately $189M in these facilities [1]. The most frequently applied method in monitoring corrosion is performing in-line inspections. In-line inspections are carried through high-tech devices such as magnetic flux which measure metal loss anomalies and are considered as time consuming and expensive. Most of the maintenance decisions for oil and gas pipelines are usually based upon the field data collected from such inspections. In addition, some standards propose maintenance intervals without addressing pipeline condition [2]. In the recent years, thanks to the advancements in data collection methods and data analysis techniques, new maintenance planning models have been developed to avoid unnecessary, time and cost consuming inspections. However, the majority of these studies are based upon condition-based or reliability-based methods in which maintenance planning is scheduled by considering pipeline deterioration profile. These methods often ignore the effect of required time for repair and maintenance arrangements and actions that could aggravate pipeline unavailability and lead to further loss of profit. In other words, due to the importance of continued operation of a gas or petroleum pipeline on a nation's economy, it is important to take account of pipeline availability as a decision criterion in the selection procedure of maintenance actions [3]. Such consideration shall be taken in addition to the associated costs, pipeline's condition or reliability level.

In that sense, the objective of this research is to develop an availability-based maintenance planning framework for gas transmission pipelines by considering system's availability jointly with reliability levels and the associated costs. This framework is based on a failure prediction model previously developed for external corrosion of gas transmission pipelines buried in Great Plains region of the US [4]. To consider the uncertainties associated with the time of external corrosion failure, a Monte Carlo simulation is performed on the failure prediction model and accordingly, the reliability profile of gas transmission pipelines is derived. In the next step, for a case study of a 24-inch pipeline, three maintenance scenarios comprising of several actions are considered through a discrete event simulation (DES). These scenarios are defined as scenario no. 1, “sleeving and replacement”, scenario no. 2, “composite wrap and replacement”, and scenario no. 3 “replacement only”. The decision criteria for the proper time of each maintenance action are based upon both considering pipeline availability due to a maintenance action and the associated costs through the proposed availability-cost indicator. This research reveals that for scenario 2, performing the corresponding maintenance actions at the service life of 30.1 and 40.5 years, respectively, could lead to the highest availability improvement per spending. In addition, the corresponding results are associated with the service life of 33.3 and 42.2 years for scenario no. 1 and 24.2 years for scenario no. 3 respectively. These results present the simulation points at which availability per spending reaches its highest level due to the initiated balance between cost and availability values. In case of maintaining a pipeline prior to the reported schedules, too frequent maintenance interventions are carried. This leads to an over maintenance due to marginal improvement in availability compared to the high maintenance costs. On the other hand, performing a maintenance action after this schedule will lead to under maintenance due to compromising pipeline availability, though cost saving may be achieved.

This research provides a novel methodology to pipeline professionals in maintenance planning of gas transmission pipelines by considering criticality of pipeline operation and availability in contrary to the existing cost-based practices. This methodology may be further expanded to other types of gas and petroleum pipelines and can help to avoid performing excessive, expensive and time consuming in-line inspections.

In this research, first a literature review on reliability-centered availability-based maintenance planning procedure and the recent efforts on maintenance planning of oil and gas pipeline is presented. Then, the pursued methodology for reliability analysis and the availability-based maintenance planning (discrete event simulation) is discussed in detail. Next, the procedure of data collection and the details on pipeline case study are presented. Finally, model implementation and analysis present the results obtained from the developed framework. The conclusions provide a summary, discussion of key assumptions and limitations, as well as avenues for future research.

2. Literature review

Failure in oil and gas pipelines may occur arising from different sources, namely, natural hazard, mechanical, operational, corrosion and third party threats [5-7]. Among these failure sources, corrosion is considered as one of the most frequent time-dependent failure type [8,9]. Only in US, more than 1700 corrosion failures have occurred for gas transmission pipelines since 1984, leading to more than $189M of property damage. Such numbers led to redirecting more attention towards the importance of proper maintenance in such facilities.

During the past years, most of the developed maintenance methods for oil and gas pipelines were merely based on inspection data related to preventive measures. Performing in-line inspections are considered as time demanding and expensive [10]. On the other hand, regarding to the suggested intervals for these inspections, the standards usually propose instructions without considering pipeline condition [2]. In the recent years, more focus has been directed towards developing maintenance planning models based on data analysis [11]. Most of these methods are considered as condition-based methodologies in which maintenance planning is scheduled regarding to the deterioration profile or reliability level of the pipeline. Parvizsedghy et al. [12] developed a maintenance planning framework based on condition thresholds for each maintenance action in addition to life cycle cost analysis (LCC). The LCC considers the uncertainties associated with operational costs and economic parameters through a Monte Carlo simulation and fuzzy approach. In two other similar studies, Sahraoui et al. [13] and Gomes et al. [14] proposed reliability-based maintenance planning strategies for corrosion failures on gas pipelines. For this objective, through referring to the available mechanical equations for the stresses acting on a pipeline and the yield strength of the steel material, the thresholds for reliability analysis were defined. In these studies, the decision criteria for inspection intervals are based on the total associated costs (i.e. the cost of repair, inspection and failure).

Li et al. [2] proposed a maintenance strategy for subsea pipelines by determining the optimal maintenance intervals from the required failure probability and its distribution. However, this research is based on some pre-assumptions for the corrosion distribution rather than real field data. Through a parametric study, Zhang and Zhou [15] estimated the optimal inspection time of natural gas pipelines prone to corrosion failures based on pre-assumptions on the distribution of failure growth rate and the total number of defects. By considering burst pressure of the pipeline as the limit state function and the expected cost as the decision criteria, the inspection interval is selected.

As one of the few studies to address pipeline availability during maintenance due to corrosion failure, Ossai et al. [16] determined different lifecycle phases of a pipeline. By considering several inspection scenarios and based on the survival function of the pipeline at different life cycle phases and availability of the pipeline, probability of failure is calculated for future. This model predicts defect growth rate and the appropriate maintenance strategy based on the defined thresholds for maintenance actions and defect growth rates. Accordingly, the costs of the maintenance plan are estimated based on the strategy selected. However, in this research, availability is not deployed as a decision criterion in pipeline maintenance planning.

The state-of-the-art review on maintenance planning of oil and gas pipelines highlight some research gaps in this field that need to be addressed. Some of these methodologies rely on performing in-line inspections or are based on simplified assumptions for failure distribution to obtain pipeline deterioration curve or probability of failure. Such methodologies are limited in application due to their dependency on parameters of specific pipelines. In addition, in most of these studies, the impact of maintenance actions on availability of a pipeline is ignored. In other words, these studies consider maintenance costs and condition or reliability thresholds as decision criteria for maintenance planning. Such approaches are ignoring the effect of mean time to repair on availability of a pipeline as a critical facility. Through a coupled cost and availability-based maintenance planning procedure, the logistics behind mean time to repair are considered in determining the maintenance time in addition to the associated costs. Performing a maintenance action before the proposed schedule will lead to over maintenance due to a marginal improvement in availability compared to considerable maintenance costs. On the other hand, performing a maintenance action after this time will lead to under maintenance due to compromising availability for cost efficiency.

This research provides a novel methodology to pipeline professionals in maintenance planning of gas transmission pipelines by considering criticality of pipeline operation and availability in contrary to the existing cost-based practices. This methodology may be further expanded to other types of gas and petroleum pipelines and can be helpful in avoiding excessive, expensive and time consuming in-line inspections.

These highlighted gaps reveal the importance of developing a maintenance planning framework for oil and gas pipelines. In such framework, continued operation (availability) of these assets should also be considered as a selection criterion next to the associated costs and condition/reliability levels. In order to develop a comprehensive framework, the reliability/deterioration profile of the pipeline shall be based on field data collected from numerous pipelines rather than limited inspection records. For this objective, in this section, a review of the principles of reliability-centered availability-based maintenance planning procedure is presented. In addition, different maintenance alternatives for gas transmission pipelines are introduced.

2.1 Reliability-centered availability-based maintenance planning

Reliability-centered maintenance (RCM) is a methodology in the application of a maintenance tool which provides two important pieces of information; criticality of an equipment and the most appropriate maintenance operation to apply [17]. In RCM, it is assumed that the inherent reliability of the equipment is a function of design and build quality [18]. This technique was designed to create a balance between the costs and benefits to select the most effective maintenance plan and is based on the principles of reliability engineering. In reliability-centered preventive maintenance procedure, it is expected to improve the lifespan of system components in the system, reduce system failure and increase its mean time to failure (MTTF) [19,20]. In this procedure, preventive maintenance schedules are assigned depending on the specified reliability levels. RCM assumes that a system carries 100% reliability at the beginning point of operation and decreases over time with a probabilistic distribution [21]. For this objective, first the reliability function of the pipeline is obtained to take advantage of the accessible failure data. Second, an availability-based maintenance technique is considered to identify maintenance scenarios to minimize system failures and increase reliability and availability.

Availability of a component is defined as the rate of up-time to the accumulation of up-time plus downtime. Availability is an indication to the probability of up-time of a component or a system and is a measure to assess how often a system is alive [20,22]. System availability can be quantified by the mean time to failure (MTTF), and the mean time to repair (MTTR) [23].

$$a_{i,j,k} = \frac{MTTF_{i,j,k}}{MTTF_{i,j,k} + MTTR} \quad \text{(Eq. 1)}$$

Where i, j and k reflect the number of systems, number of components and maintenance intervals. MTTF is obtained based on reliability analysis principles of each component in a system. In addition, MTTR is based on the average time to repair the components to be maintained.

In the case of having access to the database of failures of a component in a system, the mean time to failure (MTTF) can be obtained from the cumulative distribution function, i.e. F(t) and probability distribution function (PDF) [19];

$$F(t) = \int_0^t f(x)dx \qquad t \geq 0 \quad \text{(Eq. 2)}$$

Reliability is defined as the likelihood (probability) that a component will perform its intended function without failure for a specified period. The relationship between cumulative distribution function of failures and reliability is as follows,

$$R(t) + F(t) = 1 \quad \text{(Eq. 3)}$$

In many cases, the probability distribution function, i.e. *f(t)*, typically follows typical distributions such as normal, exponential, Weibull etc. For a Weibull distribution [24],

$$\mathrm{f(t)} = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \quad \text{(Eq. 4)}$$

$$\mathrm{R(t)} = \int_t^{\infty} f(t)dt = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \quad \text{(Eq. 5)}$$

where β and α are defined as shape and scale parameters respectively.

MTTF which is defined as the average time that an item will function before it fails, is obtained from [19,24];

$$\mathrm{MTTF} = \int_0^{\infty} t f(t)dt = \int_0^{\infty} R(t)dt \quad \text{(Eq. 6)}$$

2.2 Maintenance alternatives in gas transmission pipelines

In this research, three maintenance options are considered for availability-based reliability-centered maintenance planning of gas transmission pipelines; i.e. replacement, composite wrap repair (type A sleeving) and type B full-encirclement sleeve repair. Considered as the most common repair type, full-encirclement sleeving is not applicable to repair of offshore pipelines since it involves welding [25,26]. The sleeve may be of steel (type A or B) or composite material [25]. Type A is often applied for non-leaking defects and can be installed on the pipe without welding it to the pipe (Jaske et al., 2006). Categorized as an economical type, in composite wrap the material is normally fiberglass or carbon fiber-based and is usually applied with an adhesive [25-27]. In type B sleeving, the sleeves are fillet welded to the carrier pipe and can be used for leaking or strengthening circumferential defects (Jaske et al., 2006).

Pipeline replacement option is usually considered in cases with extensive damage or when deterioration is observed on the pipeline [28]. In some cases, pipeline repair is performed by replacing a section of pipeline with new externally coated pipe [29]. As the most economic repair solution, this replacement can either be a complete section (weld to weld) or a smaller cut out section through utilization of couplings or connectors [25,28]. In case of pipeline replacement, shutdown or isolation of the affected segment through depressurization is inevitable to cut out a cylinder [26].

3. Methodology and model development

Figure 1 presents the proposed framework for availability-based reliability-centered maintenance planning of gas transmission pipelines. First, a state of the arts review was conducted on maintenance strategies of petroleum pipelines and their corresponding limitations as described earlier. Then, failure records, data corresponding to the required repair timing and the associated costs for different maintenance actions were collected with respect to the prediction model developed by Zakikhani et al. [4]. In phase III, based on the developed failure prediction model, and use of Monte Carlo simulation, the reliability profile of a gas transmission pipeline can be obtained. Finally, in phase IV, an availability-based maintenance plan (schedule) is proposed (Figure 2). This schedule is based upon implementing discrete event simulation on different maintenance scenarios with respect to pipeline reliability profile and consideration of improvement in reliability per unit cost as criteria benchmark indicator. In the following section, the proposed methodology is discussed in details.

3.1 Reliability analysis

For availability-based maintenance planning of gas transmission pipelines, first the reliability profile of a gas pipeline is required. This profile is obtained through performing a Monte Carlo simulation with *Companion by Minitab* software on the collected failure records and the failure prediction model previously developed by Zakikhani et al. [4]. Through Monte Carlo, the uncertainties associated with external corrosion failure are considered. For such simulation, first the best-fitting distribution is extracted from the software (based on the probability plots and p-values) for each predictor variable in the model (normal or Weibull). Then by feeding the prediction model into the simulation and generation of random values for each predictor (considering its distribution), the response variable (time of failure) is extracted (more than 10,000 alterations).

To obtain the reliability profile of a gas transmission pipeline, the cumulative distribution function and reliability profile of time of failure were obtained from Monte Carlo simulation outputs. Based on the principles of reliability analysis, the best fitting distribution for the reliability profile was obtained as Weibull using MATLAB software *dfit* tool with R-square of 0.99 and root mean square (RMSE) of 0.032.

Compared to reliability distributions with a constant failure rate (such as exponential), Weibull distribution is applied to systems in which failure rate is time dependent. Therefore, use of such distribution in reliability analysis of gas transmission pipelines is consistent with nature of corrosion failure in which rate of growth is nonstationary [30,31].

3.2 Availability-based maintenance planning: gas transmission pipelines

To perform availability-based maintenance planning procedure, a discrete event simulation was performed on three maintenance scenarios for gas transmission pipelines. Each scenario consists of one or more maintenance actions, i.e. composite wrap, reinforcement sleeves or replacement as presented in table 1. The objective of this simulation is to determine the optimum time to carry a maintenance action based on both availability improvement and the associated costs which are linked together through an availability-cost indicator $(\frac{\Delta\alpha}{C})$. $\Delta\alpha$ Corresponds to the improvement in availability after and before a maintenance action while *C* corresponds to the future cost associated with a maintenance action. Such indicator is defined to prevent performing expensive actions with minor improvements in availability. The improvement in availability $(\Delta\alpha)$ is obtained from the equation below where *i* and *ii* correspond to the time before and after performing a maintenance action.

$$\Delta\alpha = \alpha_{ii} - \alpha_{i} = \frac{\mathrm{MTTF_{ii}}}{\mathrm{MTTF_{ii}} + \mathrm{MTTR}_{ii}} - \frac{\mathrm{MTTF_{i}}}{\mathrm{MTTF_{i}} + \mathrm{MTTR}_{i}} \qquad \text{(Eq. 7)}$$

Table 1. Maintenance scenarios

Maintenance scenario	Maintenance actions
1	sleeve and replacement
2	wrap and replacement
3	replacement only

The simulation advances in discrete reliability steps of 0.05 starting from 0.9 to 0.1 for each maintenance action according to its corresponding scenario. At each reliability step (R_i), the time corresponding to the reliability level (t_i) is obtained from eq. 5. In this research, the secondary reliability level (R_{ii}, after pipeline maintenance), is obtained from two simplified assumptions on improvement of reliability due to a maintenance action for repair and replacement. For repair actions (composite wrap and reinforcement sleeves), it is assumed that the secondary reliability level improvement is equal to 70% of primary reliability drop, while for replacement action this ratio is equal to 90% [12].

For repair actions (composite wrap and sleeving): $$R_{ii} = R_i + 0.7 \times (1 - R_i) \qquad \text{(Eq. 8)}$$

For replacement action: $$R_{ii} = R_i + 0.9 \times (1 - R_i) \qquad \text{(Eq. 9)}$$

After obtaining the secondary reliability level (R_{ii}), t_{ii} is obtained from eq. 5. Similar to t_i, these values are deployed in eq. 6 to obtain $MTTF_i$ and $MTTF_{ii}$ which correspond to the mean time to failure before and after performing a maintenance action.

To obtain pipeline availability from eq. 7, it is required to have access to the associated costs and repair duration data for each maintenance action respective to the pipeline age. However, according to the collected data, these values are a function of the defect size. Therefore, it is required to link the size of defect with pipeline age. For this objective, as the second assumption in this research, the maintenance planning procedure is intended for a section with length of L. In addition, the defect size at each time is assumed to be a function of its corresponding its reliability level;

$$Sd_t = L \times (1 - R_t) \qquad \text{(Eq. 10)}$$

Where Sd_t, L and R_t correspond to defect size, section length, and the reliability level at each time. Through this assumption, reliability (a function of time) will be incorporated in the developed equations associated with the required costs and timing for each maintenance action.

Finally, for each time step, the availability-cost indicator ($\Delta\alpha/C$) is obtained from MTTF, MTTR and the associated cost values, which are all a function of the corresponding time. These values are plotted against time and the point corresponding to the maximum $\Delta\alpha/C$ is determined through a polynomial interpolation among these values. Finally, after determination of the optimum maintenance time, the reliability profile is updated according to the pre-assumptions of reliability level improvements (eq. 8 and 9). For the maintenance scenarios with more than one action, after determining the optimum time for performing the first action, the same procedure is repeated to proceed with determination of the optimum time to perform the second action.

3.3 Life cycle costing

The information obtained from cost data collection corresponds to the present cost value associated with performing each maintenance action. For the decision criteria ($\Delta\alpha/C$), C corresponds to the future cost (F) of maintaining pipeline system. Future cost value for each maintenance action is obtained from transforming the present maintenance costs (derived from the linear regression analysis on the collected data) to future costs from eq. 11 through a life cycle analysis. In this equation P, i and N correspond to present cost value, inflation rate (5%) and number of interest periods (years) respectively.

$$F_N = P \times (1+i)^N \qquad \text{(Eq. 11)}$$

4. Case study

To develop the reliability profile, the data corresponding to prediction model and failure records were collected. In addition, the timing and cost data corresponding to different maintenance actions (cost and required maintenance durations) were acquired to assess pipeline availability.

The data collected for the prediction model is based on a previous study by Zakikhani et al. [4]. In this research, the authors developed an external corrosion failure prediction model for onshore pipelines located in the Great Plains region of the US through best subset regression. This region, corresponds to a vast area of the US including nine states (Montana, North Dakota, South Dakota, Wyoming, Nebraska, Kansas, Colorado, Oklahoma, Texas and New Mexico) and features flat plains [32]. The developed model is based on gas transmission pipeline failure data collected by PHMSA-pipeline and hazardous materials safety administration since 1984 [1]- and climatological data reported by national climatic data center [33]. According to PHMSA, a failure is defined as an event leading to a death or injury, a property damage of more than 50,000 USD or any other significant event.

For pipeline availability assessment, the cost and the required time data for different maintenance actions were collected through reviewing accessible industrial brochures, published articles and reports on maintenance options for gas pipelines. These data were collected for the repair types of the non-leaking defects arising from external corrosion in accordance with ASME [27], including reinforcement sleeve (type B), composite wrap (type A sleeve) and replacement. The maintenance action durations are acquired for the mean time to repair (MTTR), while the associated costs are required for calculation of availability per unit cost as the decision criterion.

The data corresponding to pipeline replacement and composite wrap repair were collected from EPA [34]. This report covers the costs and the required timing for replacement and composite wrap (type A sleeve) repairs. The cost and duration of these repair types are dependent upon the defect length and pipeline diameter. The associated costs for this repair type include labor (operator, pipeline and apprentice), equipment (composite kits butted together, coating, backhoe and sandblast) and material as well as indirect costs such as permit and inspection services. Compared to composite wrap, replacement repair imposes a supplementary cost, i.e. gas loss and purging since this technique requires pipeline shutdown and isolation. In this report, such data are presented for a 24-inch diameter pipeline with defect lengths of 6 and 234 inches.

According to OGJ [35], the timing considered for installation of a type B sleeve is an hour. On the other hand, the length of both type A and B sleeves shall be long enough to extend at least 2 inches beyond both ends of the defect and if required two or more sleeves shall be butted and joined by welding [26]. The manufacturing and welding cost for installation of a 15 cm sleeve is reported as $600. In this research by considering similar cost elements, the associated costs and required timing for replacement, composite wraps and type B reinforcement sleeves are estimated for a 24-inch diameter pipeline with different defect lengths i.e. 6, 44, 82,120,158, 196 and 234 inches (table 2). Then, through a linear regression analysis, the equations for present maintenance costs and the time required for each maintenance action are formulated as a function of defect size. These equations are presented in figures 3 and 4. Finally, the associated costs and the required time to perform a maintenance action at each time were formulated as a function of pipeline reliability (eq. 10) by assuming as section length of 10 meters for the studied case.

Table 2. Time and cost data versus defect size

	composite wrap		replacement		reinforcement sleeve	
Defect size (in)	Cost ($)	Time (hr)	Cost ($)	Time (hr)	Cost ($)	Time (hr)
6	6647	16	48208	40	5834	13

44	12592	19	49810	43	12592	15
82	19051	21	51845	47	13069	17
120	25252	24	53881	50	16725	19
158	33253	27	55917	53	21287	21
196	39455	29	57953	57	24944	23
234	45669	32	59997	60	28991	26

5. Result analysis

After formulating the associated costs and the required time for maintenance actions as a function of defect sizes (figures 3 and 4), a discrete event simulation technique is developed to determine the intervening time for different maintenance options. In this method, the decision criteria for the optimum maintenance scheduling is based on an availability-cost indicator. In availability analysis, by considering mean time to repair next to mean time to failure, failure is penalized due to accounting the time loss due to pipeline repair. On the other hand, by incorporating the associated costs as a decision factor, those maintenance options with marginal improvement in availability but excessive expenditures are penalized and avoided. Due to such considerations, the availability-cost indicator was selected as the decision factor, representing changes (improvements) in availability per unit cost spent ($\Delta\alpha/C$) performing a maintenance action.

Figure 5 and table 3 represent the time of first maintenance action for each maintenance scenario according to the maximum values of availability-cost indicator ($\Delta\alpha/C$). In case of taking a maintenance action prior to this point, an over maintenance will occur due to a marginal improvement in availability compared to the high associated maintenance costs. On the other hand, if a maintenance intervention is carried after this point, an under maintenance takes place due to compromising pipeline availability, though some cost saving may be achieved.

For scenario no. 1, the first maintenance action (sleeves) can be postponed to up to the service life of 33.3, compared to 30.1 and 24.2 years for maintenance scenarios no. 2 and 3. As presented in fig. 5, improvement of pipeline availability per unit cost for the first maintenance action of scenarios no. 1 and 2 is considerably higher than that of scenario no. 3. This points that performing merely a replacement action is not a favorable strategy in terms of improvement of availability per unit cost. Similarly, upon completion of the first maintenance action and updating the reliability profile, the optimum coupled availability-cost based schedule for the second maintenance action is determined as 42.2 years compared to 40.5 for scenario no. 1 and 2 respectively. As presented in fig. 6, pursuing maintenance scenario no. 2 (application of composite wrap) will lead to higher improvement of availability per unit cost compared to scenario no. 1.

Table 3. Maintenance action schedule obtained from discrete event simulation

Maintenance scenario	maintenance schedule (year)	
	Action 1	Action 2
1	33.3	42.2
2	30.1	40.5
3	24.2	-

In reliability-based maintenance planning, for a conservative scenario, pipeline condition shall not undergo 50% [12]. Considering this threshold, for maintenance scenario no. 1 and 2, pipeline service life will be closely extended to 79.4 and 77.7 years respectively. However, for maintenance scenario no. 3, this threshold is attained at 56 years compared to 43.9 years in case of no maintenance intervention (fig. 7). On the other hand, the results obtained from two separate discrete event simulations on the associated maintenance costs and availability improvement (C and $\Delta\alpha$), prove that for each maintenance scenario, these values increase at each time step (figures 8 and 9). Such observation indicates that for maximum availability, the maintenance action shall be performed later. On the other hand, for minimum costs, the action shall be performed sooner. Therefore, it is interpreted that consideration of a coupled-availability-cost indicator in the decision-making process, will provide a benchmark for the tradeoffs between availability and cost. Such indicator will lead to attaining the maximum availability per unit cost spent for the maintenance action, justifying the expenditures that create availability improvements.

It shall be noted that the developed reliability profile of gas transmission pipelines was validated through MATLAB *dfit* tool with R-square and root mean square error (RMSE) of 0.99 and 0.032, respectively. On the other hand, the presented life cycle cost corresponds to the specific case study. Therefore, subject to availability of data, the proposed methodology can be extended to other case studies.

6. Conclusions

In this research an availability-based reliability-centered maintenance planning framework was proposed for gas transmission pipelines. Such framework was based upon considering these pipelines as critical assets where continuity of pipeline operation (availability) is of high importance in maintenance planning, in addition to safety levels and the associated costs. The proposed framework was applied to a case study of a 24-inch (diameter) buried gas transmission pipeline. The case study was chosen in line with a previous study that developed failure prediction model for gas transmission pipelines buried in Great Plains region of the United States. Though in this research the presented results correspond to the case studied, this framework can be similarly extended to any other critical asset such as distribution or transmission oil pipelines in case of having access to the corresponding maintenance and failure prediction data. This general applicability is tied to the framework basis upon principles of life cycle cost and availability analysis that is a function of asset's mean time to failure, mean time to repair and future maintenance costs.

In the proposed framework, the cumulative distribution function of gas transmission pipeline was first developed through a Monte Carlo simulation where the model was fed by two inputs, i.e. failure prediction model and the corresponding explanatory variables. Through the principles of reliability analysis and based on the cumulative failure distribution, a Weibull reliability profile of gas transmission pipelines was developed. Three maintenance scenarios composed of different maintenance actions were defined and the corresponding data for the required timing and associated costs were collected. Then, through a discrete event simulation and by obtaining associated maintenance costs and changes in availability at each time step, improvement of availability per unit cost was derived. Finally, for each maintenance action, the maintenance time decision was made according to an availability-cost indicator.

The results of this research reveal that in terms of coupled availability-cost-based maintenance planning, the second maintenance scenario (composite wrap and replacement) is more effective. This order is followed by the first (sleeve and replacement) and the third (replacement only) maintenance scenarios respectively. Through the proposed framework, consideration of changes in availability per unit cost will provide a compensation between the improvement of availability and the associated costs. Such compensation is obtained due to the ascending order of both variables over pipeline service life. The determined maintenance schedules correspond to the points with the maximum improvement of availability per unit cost to avoid over/under maintenance.

This research provides the primary steps towards development of a novel methodology for maintaining gas transmission pipelines by considering criticality of pipeline operation and availability in contrary to the existing cost-based practices. For future research, this study can be further extended to a multi objective problem on availability and the associated costs. In addition, the rationale behind this proposed framework can further be justified by basis upon historical data au lieu of simplified assumptions. These assumptions include improvement of reliability in case of a maintenance intervention and the relationship between reliability level and the defect size. This research can be useful to researchers and practitioners by providing a new approach in maintenance planning of oil and gas pipelines where pipeline availability and continued operation is considered critical. Subject to availability of data, the proposed framework can be extended and applied to other critical asset case studies.

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