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Research Article

Pipeline Maintenance Prioritization Considering Reliability and Risk: A Conceptual Methodology

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Abstract

A concept methodology is presented in this paper to determine pipeline maintenance schedule for a multicomponent pipeline network. A simple Weibull function based failure prediction model is proposed for calculation of reliability and risk. The proposed method is demonstrated through application to a series and a mixed system of pipeline networks. The study reveals that the system definition has significant influence in the maintenance decision of multi-component systems. The reliability based approach and risk based approach provided different maintenance program for the same systems investigated. The thresholds play important roles in the decision making using the reliability and risk based approaches. A method to establish the relationship between the risk threshold and the reliability threshold for a system is presented. Such a relationship is considered useful for the decision makers in selecting the thresholds rationally and thus taking the benefit of the risk based and reliability based methods in the infrastructure maintenance program.

Keywords: Pipeline Maintenance; Prioritization; Reliability; Risk; Failure Function; Deterioration Modeling; Weibull Function

1. Introduction

Pipeline system plays an important role in the modern society through transporting oil and gas as well as municipal water and waste water. The performance of the pipeline system is affected by the deterioration due to aging. Corrosion appears to be the most significant cause of deterioration of metal pipes, accounting for up to 69.7% of pipeline failure (57.7% and 12% for internal and external corrosion, respectively, Webster 2010). Proactive maintenance of the pipeline system is required for ensuring structural integrity and improving the level of services. A number of different approaches suitable for pipeline maintenance are available in the published literature. These include qualitative assessment of risk such as failure mode and effect analysis (FMEA), hazard and operability study (HAZOP), fault tree analysis (FTA), event tree analysis (ETA) and others. Rogers

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(2011) presented a performance-based approach to estimate the present and future conditions of pipe from routine pipe inventory and break record data for prioritization of pipeline for maintenance. However, most of the technologies are not often implemented for pipeline maintenance planning due to the complexity of the models and unavailability of necessary data for model development (Jenkins et al. 2015). Pipeline operation companies often lack resources to collect data that are required for many of the models.

To address the problem, a number of stochastic degradation models are being developed for selection of optimal maintenance strategies for pipelines (Hong et al. 2014). Jenkin et al. (2015) proposed a Weibull hazard rate model for water distribution network that is applicable even if the available data are incomplete. In their model, the expert opinion of utilities professional was elicited to fill the data gap in order to develop and validate the model. The model thus requires data based calibration that may make it difficult for implementation by the users. In this paper, a simplified Weibull based failure prediction model is proposed that could be developed based on a stochastic analysis. Thus, no data based calibration would be required for the model. Expert opinions on the pipe condition can be incorporated into the model through the location parameters of Weibull function.

Most of the existing models for pipeline maintenance generally focus on a single component pipeline system. However, a pipeline network is a multicomponent system where failures of the system may be caused by many basic events leading to several dependent scenarios (Shahriar et al. 2012). A concept of pipeline maintenance prioritization is presented here considering system risk and system reliability. Detail formulation of the method will appear in Phan and Dhar (2016). The reliability and risk of pipeline system related to deterioration due to aging is only considered.

2. Modelling of Pipeline System

A pipeline system comprise a number of interconnected pipe components that results in a complex network. Fig. 1 describes the components in a natural gas delivery system where gas from wells is collected through gathering lines to compressor stations. From the compressor stations, a system of transmission lines transports gas to gate stations. Each gate station distributes gas through the distribution (normally called "mains") lines to the service lines. The system of transmission lines, "mains" and the service lines in pipeline network could be modeled as series, parallel or mixed systems depending upon system failure definitions.

For the purpose of illustration, a simple network of seven pipelines as shown in Fig. 2 is considered. The network comprises three different types of pipelines (Type I, Type II and Type III) for transmission, mains and service lines, respectively. The product (e.g. Gas) is supplied from location A to locations B, C, D and E through the system of pipelines. The pipelines of the system are considered as independent.

The system failure for the network in Fig. 2 can be defined in a number of ways. Fig. 3 shows two failure scenarios of the system failure. The corresponding system model is demonstrated in Fig. 4. In failure scenario 1 (Fig. 3a), system failure is defined when the service is interrupted to any one of the locations (either B or C or D or E). Thus, any particular component failure would result in the failure of the system. A serial model should be considered for this scenario (as shown in Fig. 4.a).

This scenario is applicable for a priority area where continuous service to each location (B, C, D, E) is desired.

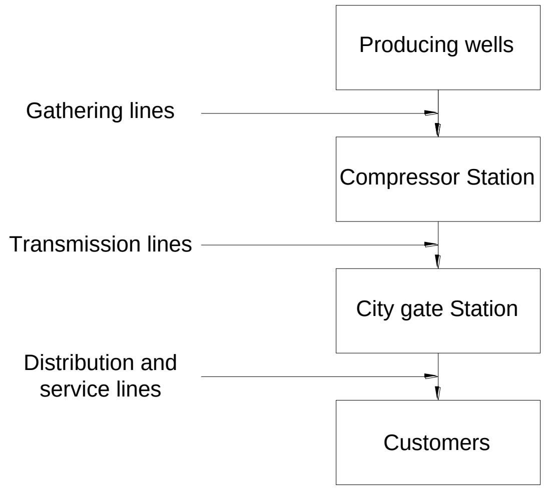


Fig. 1. Nature Gas Delivery System components

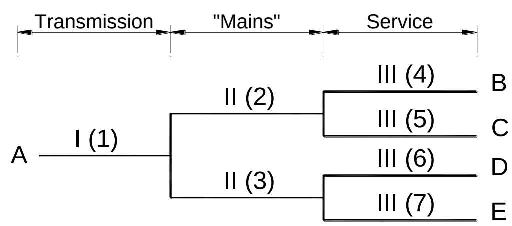
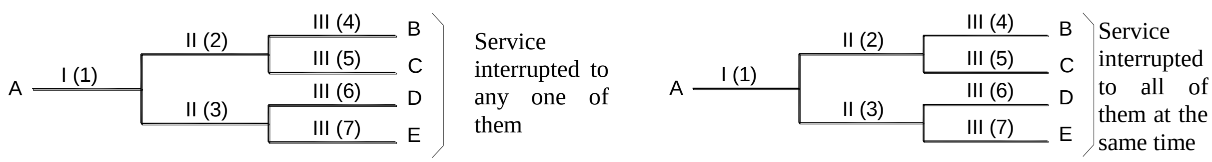


Fig. 2. An example of simple pipeline network system



(a) Series system (b) Mixed system

Fig. 3. System failure definitions

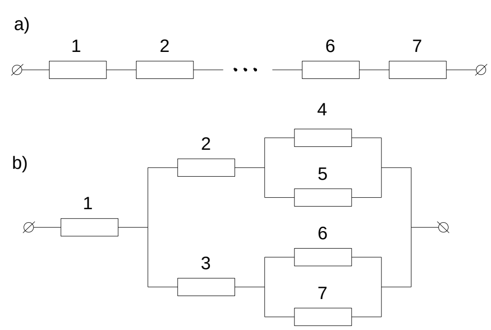


Fig. 4. System model: a) series system, and b) mixed system

Another scenario is where a system failure is considered when the services to all of the locations are interrupted at the same time. For the pipeline network in Fig. 3b, a system failure is defined when all of the service pipelines or all mains in the network fail. Thus, the transmission pipeline is in series and all other pipelines are in parallel making a series-parallel (mixed) system. The system model for this network is shown in Fig. 4b.

Reliability or survival function for a serial system, S_S and a parallel system, S_P are given by Eq. 1 and Eq. 2, respectively (Kececioglu, 2002).

$$S_S(t) = \prod_i S_i(t) \tag{1}$$

$$S_P(t) = 1 - \prod_i F_i(t) \tag{2}$$

Where, $S_S(t)$: reliability or survival function of series system at a given time t; $S_P(t)$: reliability or survival function of parallel system at a given time t; $S_i(t)$: reliability or survival function of component 'i' at a given time 't', and $F_i(t)$: failure function of component 'i' at a given time 't'.

A mixed system can be divided into series and parallel subsystems. The failure function and the survival function then calculated based on the relationship among the subsystems. For the mixed system in Fig. 4b, component 1 is in series with a subsystem including the other components. The subsystem on the other hand comprises two other parallel subsystems, one of which includes components 2, 4 and 5 and the other includes components 3, 6 and 7. Within the subsystems, component 2 is in series with two parallel components (components 4 and 5). Similarly, component 3 is in series with the parallel components 6 and 7. Applying Eq.(1) and (2) for the series and parallel components, respectively, the survival function for the system in Fig. 4(b) can be obtained as shown in Eq. 3.

$$S_{mix}(t) = S_1(t)\left\langle 1 - \left\{1 - S_2(t)\left[1 - \left(1 - S_4(t)\right)\left(1 - S_5(t)\right)\right]\right\}\right\rangle\left\langle 1 - \left\{1 - S_3(t)\left[1 - \left(1 - S_6(t)\right)\left(1 - S_7(t)\right)\right]\right\}\right\rangle \tag{3}$$

The failure function of the system is then given by:

$$F_{mix} = 1 - S_{mix} \tag{4}$$

3. Failure and Reliability Function

Modelling of time-dependent deterioration process for the development of failure function has been the focus of the researchers (i.e. Weiguo et al. 2015). This includes distribution of random variables and the types of distribution of failure. Two different distributions such as Poisson (Kleiner and Rajani, 2010) and Weibull (Teixeira et al. 2007; Mokhtar et al. 2009) distributions are commonly used for failure definitions. In this paper, Weibull function is considered for failure prediction modelling of individual pipe components. According to Weibull distribution,the probability density function of failure is given by (Eq. 5):

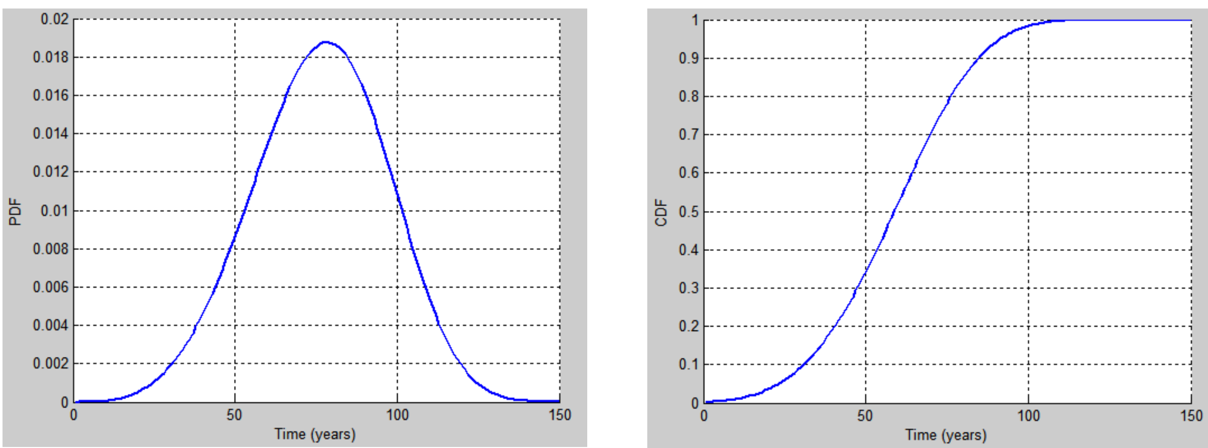
$$f_i(t)=\frac{\beta_i}{\eta_i}\left(\frac{t-\gamma_i}{\eta_i}\right)^{\beta_i-1}e^{-\left(\frac{t-\gamma_i}{\eta_i}\right)^{\beta_i}} \tag{5}$$

Based on the Weibull model, reliability function and failure function are defined using Eq.6 and Eq.7, respectively:

$$S_i(t)=e^{-\left(\frac{t-\gamma_i}{\eta_i}\right)^{\beta_i}} \tag{6}$$

$$F_i(t)=1-e^{-\left(\frac{t-\gamma_i}{\eta_i}\right)^{\beta_i}} \tag{7}$$

In the above equations, $S_i(t)$: survival function; $F_i(t)$): failure probability; β_i: shape parameter; η_i: scale parameter; and γ_i : location parameter.



a) Probability density function (PDF) b) Cumulative density function (CDF)

Fig. 5. Failure function based on Weibull parameters in Moktar et al. (2009)

Moktar et al. (2009) carried out a stochastic degradation analysis of steel pipelines and provided a Weibull function with parameters: $\beta=4.093$; $\eta=82.92$ and $\gamma=0$. Fig. 5 shows the failure function of steel pipelines based on the Weibull parameters of Moktar et al. (2009). As seen in the figure, the probability density function is normally distributed. According to the model, the cumulative failure probability reaches 100% at the age of 125 year. Similar failure function could be developed for each type of pipelines in the system (network) based on stochastic degradation analysis. In these models, the location parameter (γ) is proposed to be a variable that would be updated based on expert opinions on the pipe conditions. For example, if the expert opinion indicate a failure probability of a pipe, the time (t_E) corresponding to the failure probability is determined from the Weibull function with γ=0. Then, the location parameter, γ_i corresponding to the pipe condition can be estimated from the relation, t - γ_i = t_E, where 't' is the actual age of the pipe. The Weibull function with the estimated location parameter can be used for subsequent prediction of the failure probability or survival function.

4. Estimation of Risk

Risk is a measure of the probability and for the consequence of undesired events to represent human, environmental or economic values. It is commonly expressed as the probability of occurrence times the consequences.

In a system, there are risks for each component and the whole system. If the failure probability of the *i*th component is $F_i(t)$ at time 't' and its consequences is denoted as $C_i(t)$, the risk of the *i*th component can be expressed as:

$$R_i(t) = F_i(t)C_i(t) \tag{8}$$

The risk usually consists of direct and indirect consequences and could be expressed as:

$$R_i(t) = R_i^{dir}(t) + R_i^{ind}(t) \tag{9}$$

Similarly, the risk for a system can be defined as:

$$R_{sys}(t) = R_{sys}^{dir}(t) + R_{sys}^{ind}(t) = F_{sys}(t)\left(C_{sys}^{dir}(t) + C_{sys}^{ind}(t)\right) = \left(1 - S_{sys}(t)\right)\left(C_{sys}^{dir}(t) + C_{sys}^{ind}(t)\right) \tag{10}$$

Here, $R_i^{dir}(t)$: Risk related to direction consequences of the *i*th component at time t
$R_i^{ind}(t)$: Risk related to indirection consequences of the *i*th component at time t
$C_{sys}^{dir}(t)$: Direct consequences of the system at time 't'
$C_{sys}^{ind}(t)$: Indirect consequences of the system at time 't'
$R_{sys}(t)$: System risk
$S_{sys}(t)$: System survival probability

Direct consequences can be calculated as the cost for replacement of the failed components (or systems). Indirect consequences are much more difficult to calculate (Barone and Frangopol, 2014) because it is not only the cost for the interruption of the services but also the other effects of the failure events. For example, all including pollution, safety loss, lost of businesses reputation etc. resulting from a failure constitute indirect cost, which is difficult to be estimated.

Consequence of the system, to be used for system risk calculation, is often related to the consequences of the components. A "dynamic risk" approach is proposed here to calculate the system risk from the component consequences, as shown in Eq. 11.

$$R_{sys}(t) = \frac{\Sigma \frac{\partial F_{sys}(t)}{\partial F_i(t)} C_i\ (\mathrm{t})}{\Sigma \frac{\partial F_{sys}(t)}{\partial F_i(t)}} F_{sys}(t) \tag{11}$$

This equation reflects the contribution of consequence of each component to the overall consequence of the system. A component, at a given time t, having a higher failure probability would have higher consequence on the system.

5. Procedure for Maintenance Decision

Fig. 6 presents a flow chart for the procedure of decision making considering risk and reliability. At a given time, failure probability and risk are calculated for each pipe component and the system based on the component failure functions and the consequences. These are then compared with the corresponding threshold values. Assuming that the components were constructed at different time and have different location parameters, component failure probabilities will be different in each calculation step.

The component reliability and risk are first compared with the threshold values to identify the components requiring repair or replacement. When the component risk is lower and the reliability is higher than the threshold values, no repair or replacement is expected. When reliability and risk violate the thresholds for a particular component (i.e. component k), the time is noted, which is the time for maintenance of this component, and the component identification (ID) is recorded. The location parameter of the component is then set based on an expert opinion on the condition of the pipe (corresponding to the maintenance undertaken) to proceed with calculation for the next step.

Whenever a system threshold (risk based or reliability based) is violated, an investigation is carried out to find out the component(s) (say, component(s) “j”) which has the most significant effect on the system survival probability (and risk). To identify a component influencing the system most significantly, the age of the component is first set such as to provide 100% reliability, while the other component are at their actual age. The reliability and risk are then calculated for the system. The procedure is continued for all the components. Subsequently, the components are ranked according to the calculated reliability and risk values. The component resulting in lowest system risk and highest system reliability corresponds to the one that has most significant influence on the system at a given time.

After ranking of the components, system reliability and system risk are examined with consideration for repair/replacement of the component(s). Repair/replacement sequence is chosen from the most significantly influencing component with subsequently addition of the next component according to the rank, until the reliability and the risk criteria are met. The maintenance time and the identification (ID) of the “component(s) j” are then recorded and the location parameter for the components are set as discussed earlier.

The above steps are repeated to determine the life cycle maintenance plan for the pipeline network. Whenever a maintenance requirement is identified, details including order of maintenance, years to maintain, identification of the component, cost for maintenance and cumulative cost are recorded. After every maintenance program, location parameters for each component are changed based on the condition of the pipe (according to expert opinion) for the determination of next maintenance plan. A program using Matlab is developed for the calculations.

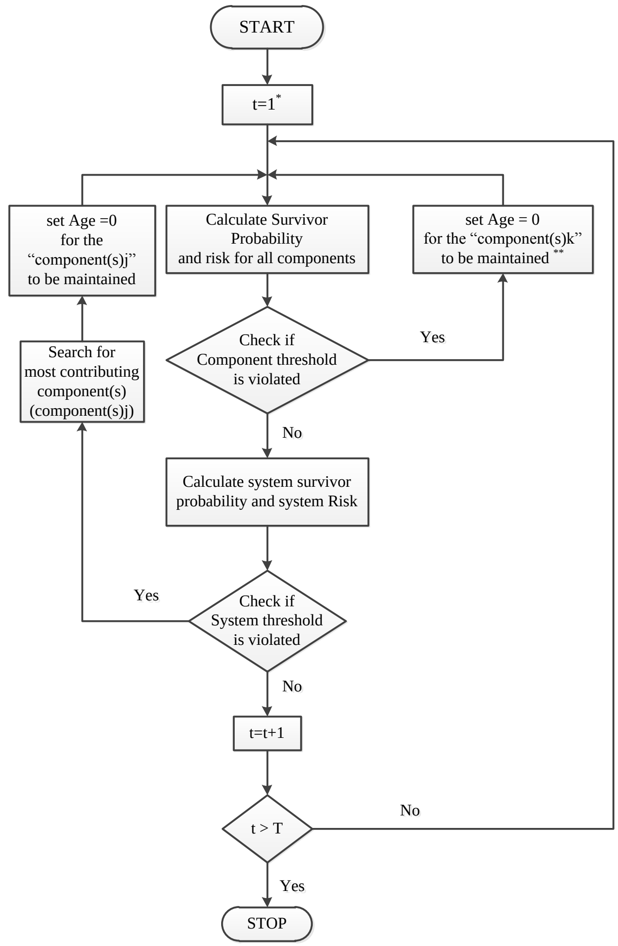
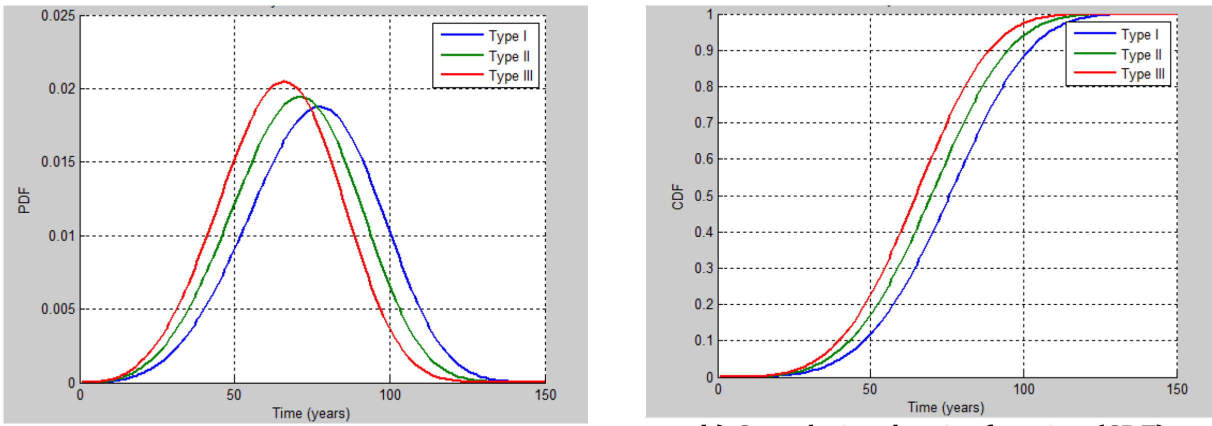


Fig. 6. Flow charts for the reliability and risk based approach

6. Numerical Examples

To illustrate a pipeline prioritization program for maintenance, a series configuration in Fig. 4a and a mixed configuration (as in Fig. 4b) are considered. As discussed earlier, the system has three different types of pipes, i.e. Types I, II, III for transmission, "main" and service lines, respectively. Each component (type of pipe) is assumed to be at different age and have different failure functions. Failure function for pipeline components were chosen based on the Weibull parameters of Moktar et al. (2009). Table 1 shows the Weibull parameters chosen and the consequences assumed for the pipe components. Fig. 7 illustrates the probability density functions (PDF) and the cumulative distribution functions (CDF) for pipeline Types I, II and III. As shown in the figure, CDFs for all pipes are almost the same up to 20 years of age and are negligible. All three types reach 100% of failure probability after 125 years.The direct and indirect costs are also assumed arbitrary for the example stated here (Table 1). Indirect cost consequences are assumed to be higher than the direct cost consequences.



a) Probability density function (PDF) b) Cumulative density function (CDF)

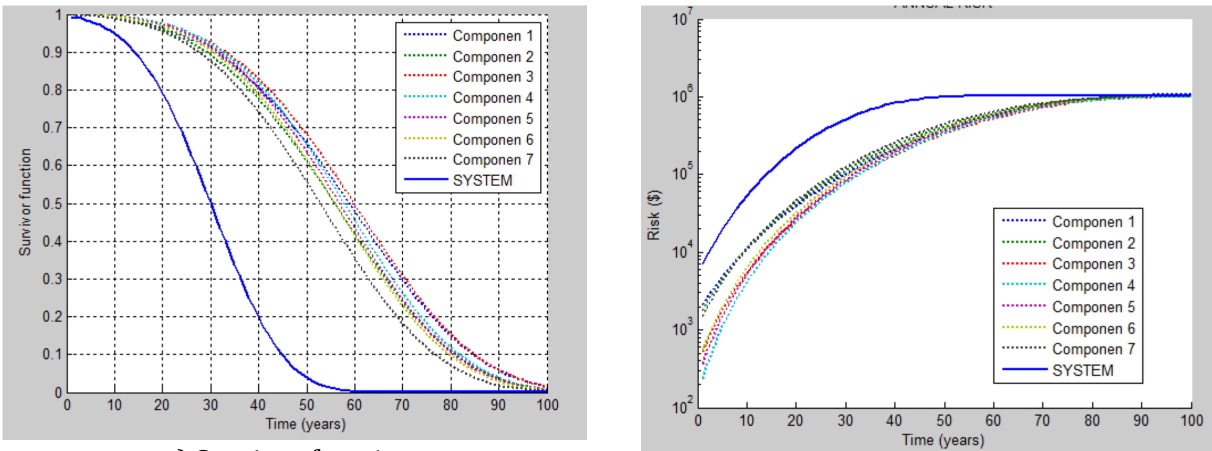
Fig. 7. Failure probability distribution for pipelines

Table 1 Parameter for the pipeline component

Component	Type	η_i	β_i	Age (yr)	C_i^{dir}	C_i^{ind}
1	I	82.922	4.093	18	10e4	1e6
2	II	76.691	3.907	15	5e4	1e6
3	II	76.691	3.907	11	5e4	1e6
4	III	71.346	3.826	8	1e4	1e6
5	III	71.346	3.826	9	1e4	1e6
6	III	71.346	3.826	10	1e4	1e6
7	III	71.346	3.826	13	1e4	1e6

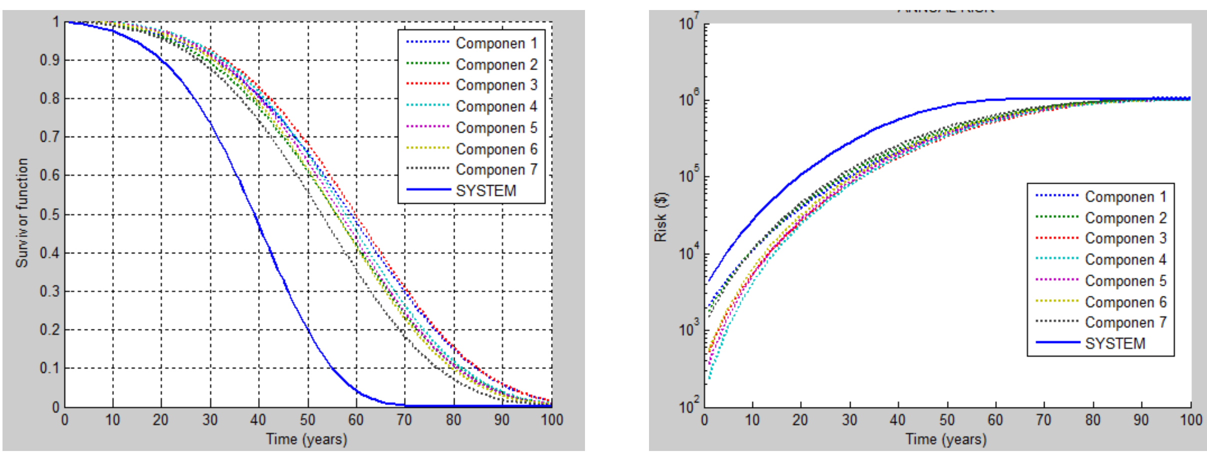
Fig. 8 and 9 show the survival functions and the risks for a series and mixed system (Fig. 4), respectively. The figures reveal that the survivor probabilities with different systems configurations are different. The survivor probability of series system decreases to zero at 60 year (Fig.8a) while for mixed system it reaches to zero at 70 year (Fig.9a). In the both cases, the survival probabilities of the systems are always lower than those of the components. This may be due to the fact that both systems include a series component (i.e. in the mixed system, component 1 is serially connected to a sub-system components 2 to 7). Survival function for the components reaches to zero after 100 years. The system and component risks (Fig. 8b and 9b) increases nonlinearly until the survival probability reach to zero. The system risks are also higher than the component risks for the both cases.

Four cases with different reliability and risk thresholds (Table 2) are assessed for the serial and mixed systems defined in Fig. 4. Fig. 10 presents the calculated results of the survival functions and risks for the series system with the threshold values of survivor probabilities (case 1 in Table 2).



a) Survivor functions b) Risk

Fig. 8. Survival functions and risks for the series system



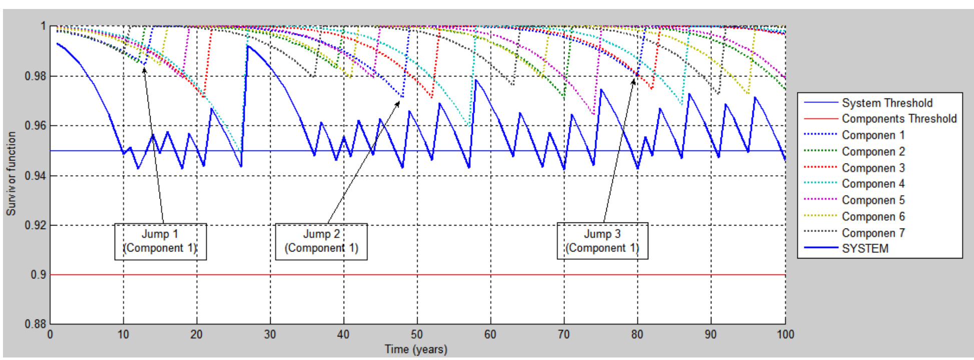
a) Survival functions b) Risk

Fig. 9. Survival functions and risks for the mixed system

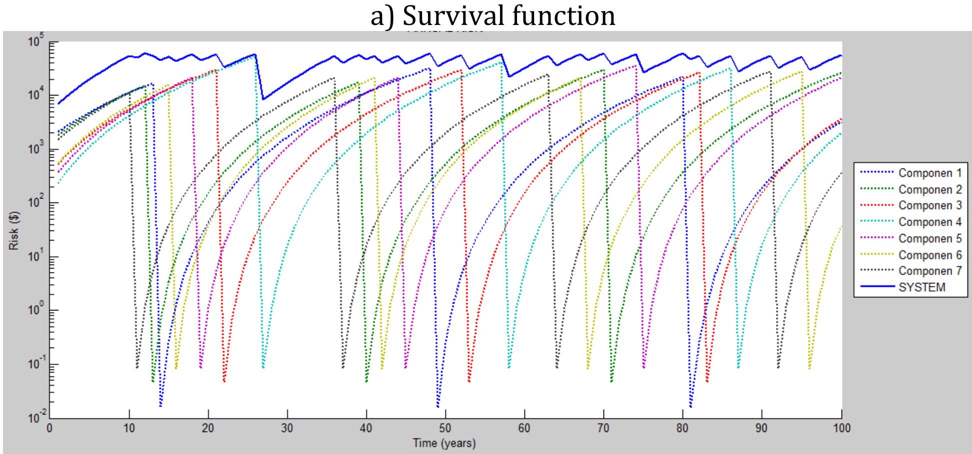
Table 2 Reliability and Risk Thresholds

Case	Type of system	Type of threshold	System threshold	Component threshold
Case 1	Serial	Survivor probability (%)	95	90
Case 2	Mixed	Survivor probability (%)	95	90
Case 3	Serial	Risk ($)	200,000	200,000
Case 4	Mixed	Risk ($)	200,000	200,000

System reliability appears to control the maintenance schedule in Fig. 10(a) because of the characteristic of the serial system. As observed above, failure probability of system is always higher or equal to the component failure probabilitiesfor a series system. The survival probabilities of every component are thus consistently above the system threshold (i.e. 95%). When the system threshold due to a component is reached or exceeded, a repair/maintenance is assumed for this component and a new location parameter is assigned to the component (as discussed earlier). A location parameter corresponding to 100% survival probability is used after each repair/maintenance for the examples presented here. This is indicated by the jumps in the survival functions in Fig. 10(a). Every jump in the survival function for each component corresponds to a maintenance that also results in a jump to the system survival function. The maintenance schedule and the number of maintenance requirements for the components can be obtained from Fig. 10(a) with the elapsed time and the number of jumps, respectively. For example, component 1 has 3 jumps, shown in Fig. 10(a), at the elapsed time of 13 year, 48 year and 80 year, respectively. A total of three maintenance actions are therefore expected for the component to be carried out at the ages of 13 year, 48 year and 80 year, respectively, if each maintenance work bring the pipe to the state of a new pipe (i.e. 100% reliability). The estimated maintenance schedule for the pipeline components for this system is summarized in Table 3, including the year to repair/maintain and the components to be repaired/ maintained. A total of 24 repairs are estimated over a period of 100 year for this system considered in this example.



a) Survival function



b) Annual risk

Fig. 10. Reliabilities and risks of series system with application of survival threshold (case 1)

Annual risks for this case (case1) with the reliability based maintenance are calculated as demonstrated in Fig. 10(b). Due to the consideration of the dynamic risk, discussed earlier, at each step of calculation, the risk values change while reliability thresholds are constant. The maximum risk is calculated to be $6x10^4$. This maximum risk is not compared with any threshold for this case of reliability based maintenance of the series system.

Table 3 Maintenance Schedule for series system with reliability thresholds (case 1)

Maintenance counts	1	2	3	4	5	6	7	8	9	10	11	12
Year to maintain	10	12	13	15	18	21	26	36	39	41	44	48
Component to maintain	7	2	1	6	5	3	4	7	2	6	5	1
Maintenance counts (cont.)	13	14	15	16	17	18	19	20	21	22	23	24
Year to maintain	52	57	63	67	70	74	80	82	86	91	95	100
Component to maintain	3	4	7	6	2	5	1	3	4	7	6	2

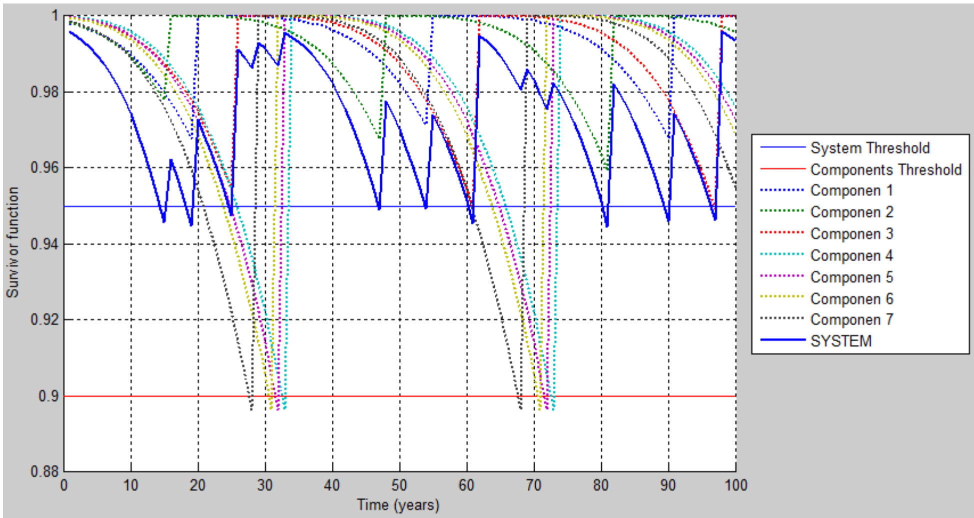
Fig. 10(b) shows non-zero risk level even for the components undergoing maintenance (survival function set to 100% through setting of the location parameter). This is due to the fact that the figure shows the risk at one year after the maintenance (i.e the following year when the failure probability is non-zero).

Fig. 11 shows the results of reliability based assessment of the mixed system (Case 2). Both system reliability and component reliability appear to control the maintenance schedule for this system. The component survival function approaches the threshold of 90% and the system survivor function approaches the threshold of 95% in a few cases in Fig. 11(a). Survivor probabilities of components 4, 5, 6 and 7 reduced to 90% at around the 30th year and the 70th year, when the system survivor probability was remained within the threshold value. Fig. 11(b) shows how risk of the system and the components in this case (Case 2) changes with maintenance of the mixed system based on the reliability. The maximum risk for the component was calculated to be $10.45x10^4at the 32nd year. The corresponding risk for the system was as low as $1.4x10^4$. The calculated maintenance schedule for this case is presented in Table 4. The number of maintenance requirement for the mixed system (i.e. 17) is found to be less than that for the series system (i.e. 24), discussed above.

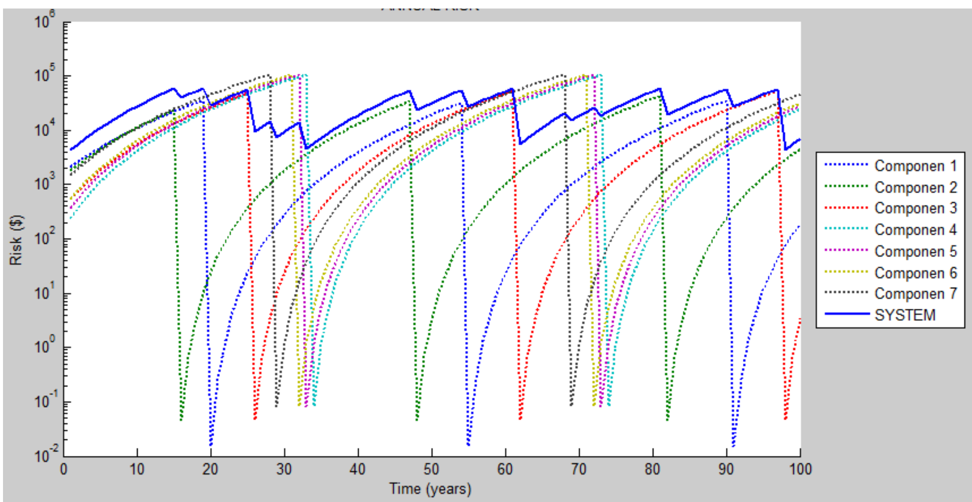
Table 4 Maintenance Schedule for Mixed System with Reliability Thresholds (Case 2)

Maintenance Counts	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Year to maintain	15	19	25	28	31	32	33	47	54	61	68	71	72	73	81	90	97
Component to maintain	2	1	3	7	6	5	4	2	1	3	7	6	5	4	2	1	3

It is seen in the reliability based maintenance approach discussed above (for Case 1 and 2) that the maximum risks are less than the risk threshold arbitrarily assumed for Case 3 and Case 4 (Table 2). In Cases 1 and 2, the maximum risks are calculated to be $6.03x10^4$ and $10.04x10^4$, respectively whereas the risk thresholds for Cases 5 and 6 are $20x10^4$ and $50x10^4$ for the component and the system, respectively. This implies that if the risk thresholds in a risk based approach are selected without consideration for the reliability, it may result in an un-conservative maintenance program.



a) Survival function



b) Annual risk

Fig. 11. Mixed system with application of survivor threshold (Case 2)

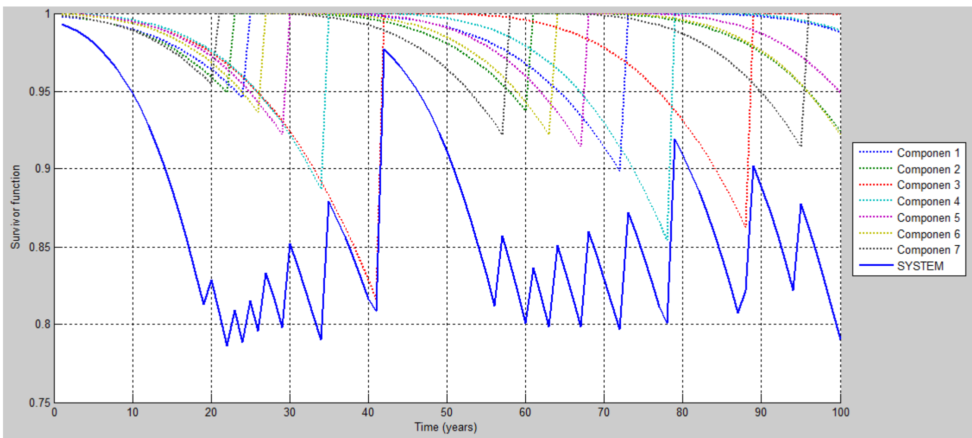
The result of risk based evaluation for the series system (Case 3) is shown in Fig. 12 and Table 5. Number of repair/maintenance requirement for series system using the risk based approach (i.e. 16) is found to be less than those given by reliability based approach discussed earlier (i.e. 24 for case 1). The lower number of maintenance requirement in the risk based approach is attributed to the use of high risk threshold (than the maximum risk calculated for Case 1).

Fig. 12(a) reveals that the system survival function and component survival function for this case reduced to around 80%. Thus the maintenance schedule obtained using the risk based method (Table 5), provided an un-conservative maintenance program.

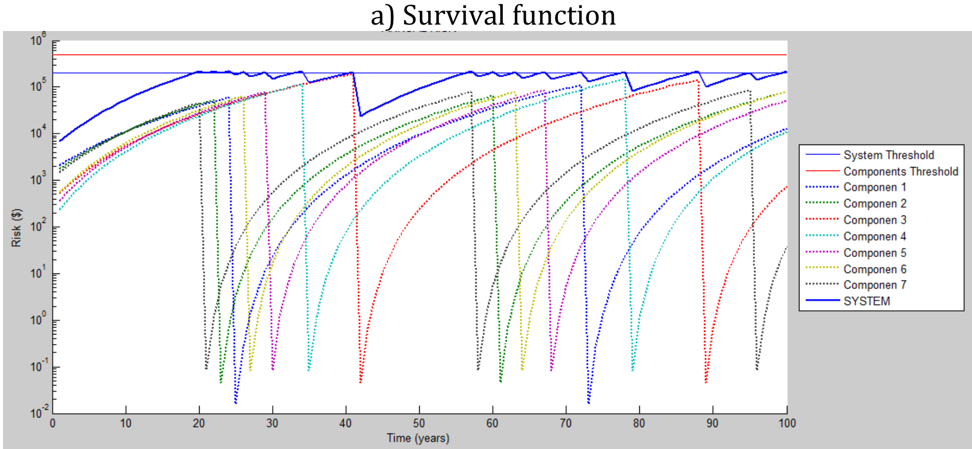
The sequence of component maintenance is also found to be different if the two different approaches (reliability and the risk based approaches) are used. For example, Table 3 (reliability based approach) indicates that pipe component 3 is to be repaired before pipe component 4, after 21 and 26 year, respectively. However, Table 5 implied that pipe component 4 is to be repaired before pipe component 3 after 34 year and 41 year, respectively.

Table 5 Maintenance Schedule for series system with risk threshold (Case 3)

Maintenance counts	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Year to maintain	20	22	24	26	29	34	41	57	60	63	67	72	78	88	95	100
Component to maintain	7	2	1	6	5	4	3	7	2	6	5	1	4	3	7	6



a) Survival function



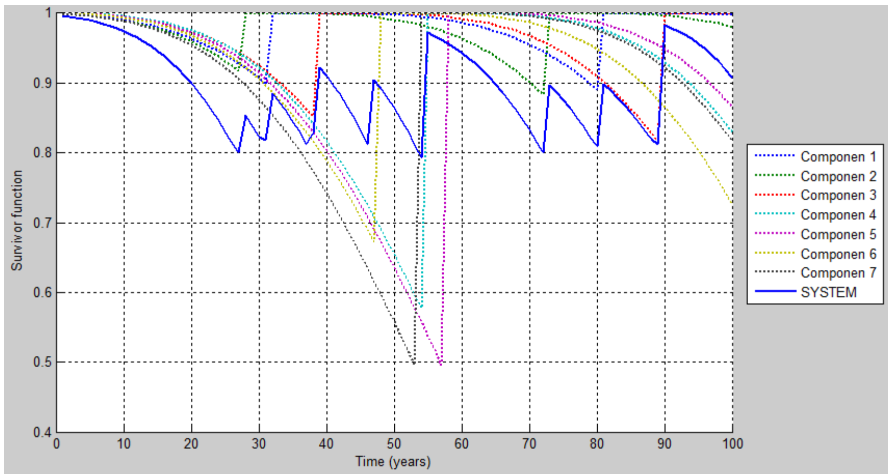
b) Annual risk

Fig. 12. Series system with application of risk threshold (Case 3)

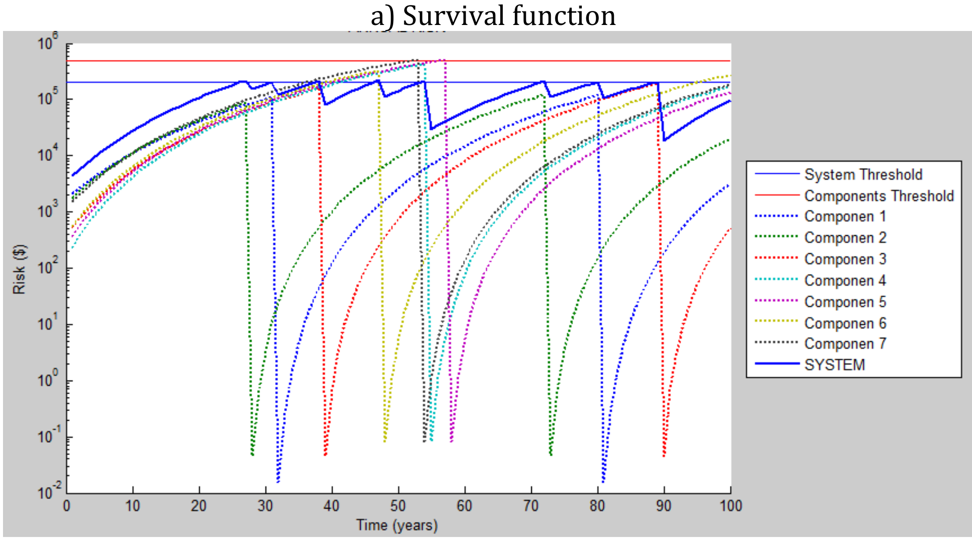
Similar results are obtained for the mixed system using the risk based method (Fig. 13 and Table 6). The number of maintenance requirement is less in this method (i.e. 10) compared to reliability based method (i.e. 17 for Case 2). The reliability of the system and the component are also less (Fig. 13a). Survival function for components 5 and 7 reaches to 50% in Fig. 13a.

Table 6 Maintenance Schedule for mixed system with risk threshold (Case 4)

Maintenance counts	1	2	3	4	5	6	7	8	9	10
Year to maintain	27	31	38	47	53	54	57	72	80	89
Component to maintain	2	1	3	6	7	4	5	2	1	3



a) Survival function



b) Annual risk

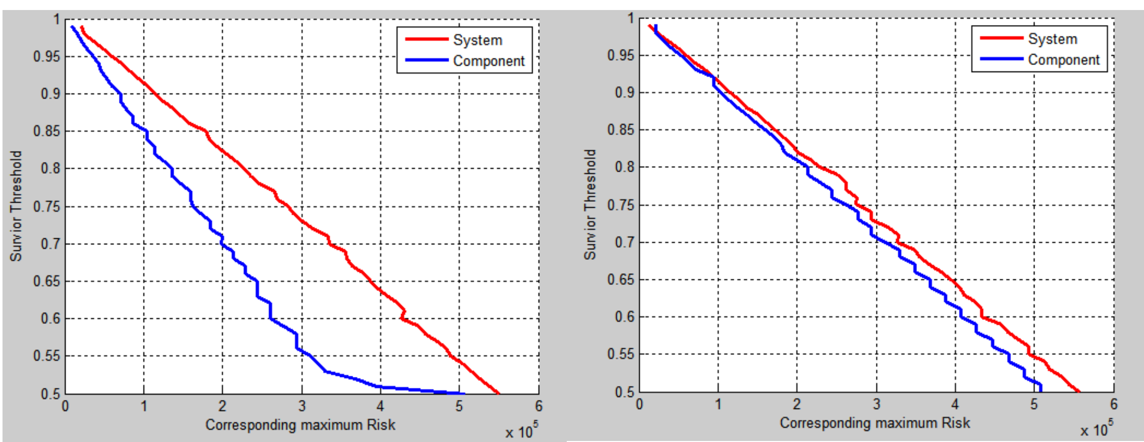
Fig. 13. Mixed system with application of risk threshold (Case 4)

7. Relation between Risk and Reliability Thresholds

The numerical examples discussed above reveal that different pipeline maintenance programs can be obtained if two different approaches (risk based approach or reliability based approach) are used. When the risk based method with high risk threshold is applied, the resulting maintenance program might be unreliable. On the other hand, the reliability based approach is unable to incorporate the consequence and the importance in the decision process. Thus, an integration of reliability and risk in the decision process would optimize the infrastructure maintenance program. Thresholds for the reliability and risk are found to play a significant role in the decision process using the reliability and risk based approaches. These thresholds could be chosen carefully to optimize the reliability and the risk. In this regards, a relationship between the risk threshold and the reliability threshold can be established for each system that could be used by the decision makers.

The relationship between the reliability threshold and the risk threshold for the series and the parallel system (Fig. 4) are shown in Fig. 14. To develop the relation, survival threshold is increased in steps from 0.5 to 0.99 and the risk is calculated using Eq. (10). The maximum of the risks over a period of 100 years is taken as the risk threshold. System threshold and component threshold are considered to be the same in this exercise.

Fig. 14 reveals linear relationships between the risk and the reliability thresholds, except for the components in the series system. As expected, a lower risk threshold corresponds to a higher reliability threshold. A survivor threshold of 0.99 corresponds to a risk threshold close to zero. For a particular value of reliability threshold, component risk threshold is lower than system risk threshold. The relationship between the reliability threshold and risk threshold is expected to vary from system to system and should be established for each system.



a) Series system b) Mixed system

Fig. 14. Relationship between survival probability threshold and risk threshold

The relationship between the thresholds discussed above would be useful in taking the benefit of the risk based and reliability based methods in the infrastructure maintenance planning through selecting appropriate thresholds. The reliability based method is a useful approach in term of engineering-safety assessment while the risk based method offers optimization the maintenance program incorporating the consequence. However, use of independent thresholds in each method may results in an unexpected outcome. A relationship as shown in Fig. 14 can be used to choose the thresholds in a rational way.

8. Conclusion

This paper presents a procedure for prioritizing pipelines for maintenance considering reliability and risk. Pipeline deterioration due to aging is only considered for the maintenance planning. A simple Weibull function is proposed to model the failure probability that can be developed based on stochastic degradation analyses. A method is proposed for updating the model incorporating expert opinions on the pipe conditions, without any requirement for data mining exercise. The proposed methods are demonstrated through examples of a series and a mixed system of pipeline networks. The study reveals that the system definition (series, parallel or mixed) plays an important role in the infrastructure maintenance decision.

The reliability and risk based approaches with independent thresholds appears to provide different maintenance program for the same system. The risk based assessment in the presented examples provided un-conservative maintenance schedule for the pipeline components with the component reliability as low as 50%. The un-conservative estimation is attributed to the use of high risk threshold.

Thresholds for the reliability and risk are found to govern the decision process in the reliability and risk based approaches. In this regard, a careful determination of the thresholds is required to optimize the decision process considering both the reliability and the risk. A method is proposed here to establish the relationship between the risk threshold and the reliability threshold for a system. The relationship between the thresholds would be useful for the decision makers in selecting the thresholds rationally and thus taking the benefit of the risk based and reliability based methods in the infrastructure maintenance planning.

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Conflict of Interest

None

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