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# Modeling Deterioration and Managing Failure Risk of Buried Critical Infrastructure

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**Abstract.** The lack of sufficient historical data on the deterioration of buried critical infrastructure such as large-diameter transmission water mains and trunk sewers is an obstacle to formulating an effective strategy for managing its failure risk. These historical data are required to model rates of deterioration in order to anticipate and prevent future failures without resorting to frequent inspections that are both very costly and disruptive.

At the National Research Council of Canada (NRC) we have developed a new fuzzy-based approach to model the deterioration of buried critical infrastructure using scarce data. Fuzzy synthetic evaluation is used to discern the 'condition rating' of an asset by aggregating the effects of various distress indicators observed (or estimated) during inspection. A rule-based fuzzy Markov model is used to replicate and predict the possibility of failure. The possibility of failure is combined with fuzzy failure consequences to obtain the fuzzy risk of failure throughout the life of the asset. The fuzzy risk model can be used to plan the renewal of the asset subject to maximum risk tolerance. Additionally, renewal strategies that could include various technologies as well as various scheduling schemes can be compared on discounted costs and maximum risk, to arrive at decisions that are commensurate with the preferences of the decision maker. The concepts are demonstrated using data obtained for a prestressed concrete cylinder pipe (PCCP). Results are discussed as well as model limitations and future research needs.

This paper provides a summary of the research. Technical details have been published elsewhere in refereed journals as well as conferences. The research was conducted with financial support from the American Water Works Association Research Foundation (AwwaRF) and NRC.

**Keywords**: Large-diameter pipes, deterioration modeling, condition rating, fuzzy sets, fuzzy Markov, failure risk, inspection scheduling, residual life, renewal strategies.

## 1. Introduction

The condition rating and the deterioration modeling of large, buried infrastructure assets, such as water transmission mains and trunk sewers is a challenging undertaking. While failure of such assets can be disastrous, low rates of failure, high costs of inspection/condition assessment and lack of robust inspection technologies result in a severe scarcity of necessary data. To compound the problem, these large assets often have no built-in redundancy to accommodate loss of service; operators are therefore generally very resistant to taking them out of service for inspection. Nonetheless, the failure risk of these pipes must be evaluated and managed, requiring a deterioration model to enable the forecast of the asset condition as well as the possibility of its failure.

The use of Markov deterioration process to modeling infrastructure asset deterioration is not new, as exemplified by [1] [2] [3] [4]. Rajani *et al.* [5] and Kleiner *et al.* [6], [7] introduced a new approach to model the deterioration of buried infrastructure, using a fuzzy rule-based, non-homogeneous Markov process. This approach took advantage of the robustness of the Markov process and the flexibility of the fuzzy-based techniques, which seem to be particularly suited to modeling the condition rating as well as the deterioration of infrastructure assets, for which data are scarce and cause-effect knowledge is imprecise or vague. The proposed deterioration model yields a possibility mass function (as opposed to probability) of failure at every point along the life of the asset. The possibility of failure is then coupled with failure consequence to obtain failure risk as a function of age. The post-renewal deterioration rate is then assessed and a rational decision can be made on when to schedule the subsequent inspection/condition assessment, when to renew a deteriorated asset, and how to select the most economical renewal alternative based on predefined maximum risk tolerance. Strategies can be further explored [8] to consider tradeoffs between cost of renewal and maximum risk to which the asset is subjected.

In this paper, the approach is described and demonstrated with an example. Technical details are provided elsewhere. The rest of this paper is organised as follows: Section 2 provides a brief introduction to the fuzzy rule-based, non-homogeneous Markov deterioration model, Section 3 presents the concept of fuzzy risk of failure, section 4 describes decision making, Section 5 presents and example and Chapter 6 provides a summary.

## 2. Failure Risk of Large Buried Infrastructure – Modeling Approach

### *2.1. Fuzzy Sets and Fuzzy Techniques*

Fuzzy-based modeling was deemed an attractive approach because: a) the interpretation of distress indicators, observed through inspection or non destructive evaluation (NDE), into a condition rating involves subjective judgment, and fuzzy sets with their notion of membership functions are appropriate for accommodating this subjectivity; b) practitioners have an intuitive understanding of the deterioration process of buried infrastructure (although many of the relationships between cause and effect are not well understood let alone quantified) and fuzzy techniques seem well suited to represent this intuition as well; c) failure of a large-buried asset is a relatively rare event and data on the consequences in terms of direct, indirect and social costs are scarce. The fuzzy approach is therefore well suited to exploit the qualitative understanding many practitioners have about the conditions that affect these costs

### *2.2. Encoding Pipe Condition as a Fuzzy Set Using Fuzzy Synthetic Evaluation*

The Markovian deterioration process requires that the condition of the deteriorating asset be encoded as an ordinal condition state (e.g., S*tate 1, State 2, or Excellent, Good, Fair,* etc.). The condition assessment of a large buried pipe comprises two steps. The first step involves the inspection of the asset using direct observation (visual, video) and/or NDE techniques (radar, sonar, ultrasound, sound emissions, eddy currents, etc.), which reveal distress indicators. The second step involves the interpretation of these distress indicators to determine the condition rating of the asset. As stated earlier, this interpretation process, which is dependent upon the inspection technique, is often imprecise and can be influenced by subjective judgment.

**Table 1.** Distress indicator that influence pipe condition for PCCP water mains

| **Category (Level 1)** | **(*j*)** | **Distress indicator (Level 2)** | **(*i,j*)** | **Comment** |
|---|---|---|---|---|
| **Mortar coating** | 1 | Spalling | 1,1 | Spalling is often a first indicator of corrosion. Large area may indicate that corrosion is taking place over a significant surface area of pipe exterior. |
| | | Crack type | 2,1 | Circumferential cracks indicate some type of longitudinal movement has taken place. Longitudinal cracks occur due to low hoop resistance (wire breaks?). |
| | | Crack width | 3,1 | Crack width is another indicator of severity of spalling. Large widths mean that spalling is imminent. |
| | | Crack density (frequency) | 4,1 | Closer crack spacing usually means the pipe is under higher stress. |
| | | Coloration | 5,1 | Signs of color/stains on concrete exterior indicate that corrosion is taking place. Often stains are precursors to spalling, i.e., corrosion products have built up. |
| **Prestressed wire** | 2 | Wire breaks | 1,2 | As the no of wire breaks increase the factor of safety decreases and eventually leads to pipe failure. |
| **Concrete core** | 3 | Delamination | 1,3 | Delamination occurs when there is poor bonding between concrete/wire or steel/steel cylinder. This can also occur when prestressing is lost due to wire breaks. |
| | | Crack type | 2,3 | Circumferential cracks indicate some type of longitudinal movement has taken place. Longitudinal cracks occur due to low hoop resistance (wire breaks?). |
| | | Crack width | 3,3 | Crack width is another indicator of severity of spalling. Large widths mean that spalling is imminent. |
| | | Crack density (frequency) | 4,3 | Closer crack spacing usually means the pipe is under higher stress. |
| | | Hammer tapping sound | 5,3 | Hammer tapping sounds can indicate delamination. It can be simple as tapping a hammer or using 'pulse echo' method. |
| | | Hollow area | 6,3 | Aerial extent of hollow sound heard can give an idea of the seriousness of the lamination (in comparison to pipe surface area). |
| **Pipe geometry** | 4 | Out of roundness | 1,4 | Out-of-roundness is another indicator of wire loss that may not be evident from concrete spalling or presence of corrosion products, etc. |
| **Joint** | 5 | Change in alignment | 1,5 | Changes in joint alignment indicate pipe susceptible to ground movement. Eventually it can lead to weld failures and hence joint failure. |
| | | Joint (internal) displacement | 2,5 | Joints can displace without undergoing joint misalignment and hence also an indicator of other forces at play. |
| | | Joint diaper crack size | 3,5 | Crack of external diaper can give an idea of joint quality. |

A method was developed by Rajani *et al*. [5] to interpret distress indicators into a condition rating, using a fuzzy synthetic evaluation technique. The factors that contribute to pipe deterioration are organized in a two-level hierarchical structure. Level 1 consists of categories, while level 2 comprises actual distress indicators. Each distress indicator provides partial evidence (hint or contribution) to the condition of the specific pipe component (level 1 category). In turn, each category provides partial evidence to support the expected condition rating of the asset. The contribution of each distress indicator towards a specific category, as well as the contribution of each category towards the final condition rating, is assessed from well-documented case histories as well as from known behaviour and performance of buried pipes, engineering judgment and expert knowledge. Table 1 provides an example of distress indicators and categories used to assess condition ratings of prestressed concrete cylinder pipe (PCCP). The contribution of each distress indicator towards its respective category can be expressed linguistically or numerically, depending on its nature and available data.

The condition rating of the asset is expressed as a fuzzy set (or possibility mass function), where the condition of the pipe is rated in terms of membership values to a seven grade scale: *Excellent, Good, Adequate, Fair, Poor, Bad, Failed*. For example, the condition rating (0, 0, 0.2, 0.7, 0.1, 0, 0) means 0.2, 0.7 and 0.1 memberships to condition states *Adequate*, *Fair* and *Poor* respectively, as is illustrated in Figure 1.

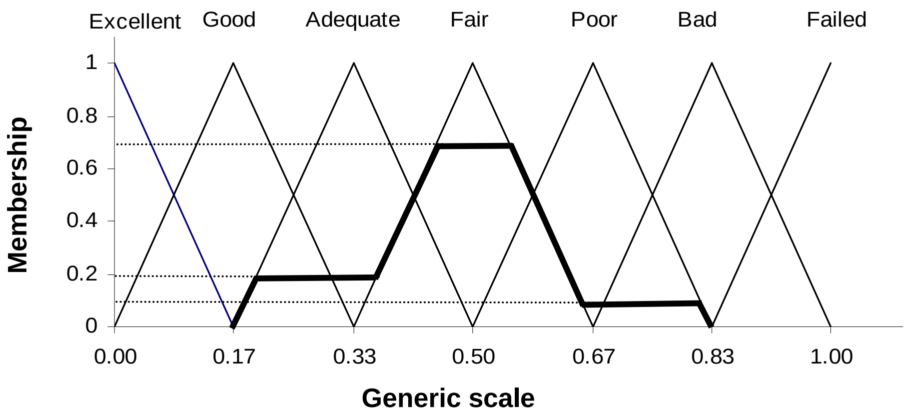


**Figure 1.** An example illustrating a fuzzy condition rating

### *2.3. Fuzzy Markov Based Deterioration Model*

The deterioration of large-diameter transmission mains was modeled using a fuzzy rule-based, non-homogeneous Markov process [6]. This approach exploits the robustness of the Markov process and the flexibility of the rule-based fuzzy techniques and their ability to handle imprecise and vague data. In the proposed model, the life of the pipe is discretized into time steps and the Markov process is applied at each time step in two stages. In the first stage, the deterioration rate at the specific time step is inferred from the asset age and condition rating using a fuzzy rule-based algorithm. In the next stage, the condition rating of the asset in the next time step is calculated from present condition state and deterioration rate. Essentially the deterioration process models the asset as it gradually undergoes change from better to worse condition states. This is done through memberships ‘flowing’ from higher to lower condition states. Using threshold values concept [6], the process is formulated to mimic a reality in which a given asset at a given time cannot have significant membership values to more than two or three contiguous condition states. Figure 2 illustrates how a pipe might deteriorate from condition (0.14, 0.59, 0.27, 0, 0, 0, 0) in year 20 to (0, 0.1, 0.38, 0.52, 0, 0, 0) in year 40.

This deterioration model yields the possibility of failure at every time step along the life of the pipe. A first step to use the deterioration model is to train (calibrate) it on condition rating(s) of a specific pipe, obtained from one or more inspections. Once the deterioration model has been trained, it can be used to predict the future condition of the pipe.

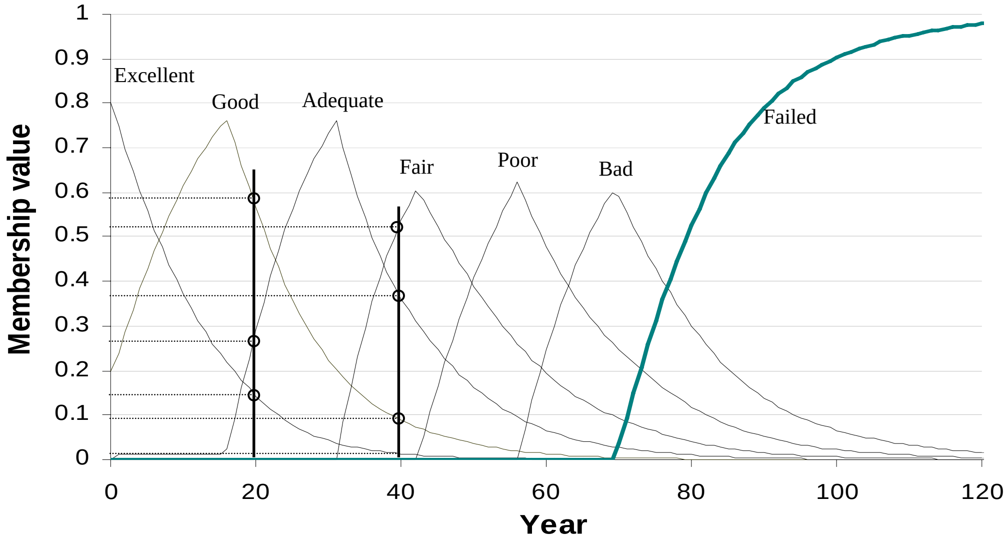


**Figure 2.** Deterioration curves

### *2.4. Post-Renewal Condition Improvement and Subsequent Deterioration*

A pipe can be repaired or renewed (rehabilitated) when the need arises. A repair is assumed to be a very localized intervention that does not improve the condition rating of the pipe by a noticeable amount, and is not likely to change the deterioration rate of the pipe. Renewal is assumed to be an intervention that improves the condition of the pipe and possibly modifies its deterioration rate as well. Consequently, the deterioration rate obtained from training the model on past inspections will be altered by a renewal but not a repair event.

Usually, several pipe renewal technologies are available, each of which is assumed to have three specific attributes [6]. The first is a condition improvement matrix, which determines how much the condition of the pipe will improve immediately after renewal. The second is a post-renewal deterioration rate matrix, which determines how fast the pipe will continue to deteriorate after renewal. The third is the cost associated with the renewal alternative. The condition improvement matrix can be populated based on hard field data, however until these types of data become available, this matrix is established from expert opinion, as illustrated in Table 1. Similarly, the post-renewal deterioration rate matrix is also estimated from experience and expert opinion, as illustrated in Table 2. Renewal costs can usually be obtained from manufacturers/contractors.

**Table 2.** Expert input to construct condition improvement matrix

| **Expression of confidence to get condition shift** | **To condition** | | | | | | |
|---|---|---|---|---|---|---|---|
| **From condition** | **Excellent** | **Good** | **Adequate** | **Fair** | **Poor** | **Bad** | **Failed** |
| **Excellent** | Highest | | | | | | |
| **Good** | Highest | Lowest | | | | | |
| **Adequate** | Medium | Highest | Lowest | | | | |
| **Fair** | Medium | Highest | Medium | | | | |
| **Poor** | Lowest | Highest | Medium | | | | |
| **Bad** | | Medium | Highest | Lowest | | | |
| **Failed** | | Lowest | Highest | Medium | | | |

**Table 3.** Expert input for evaluating the post-renewal deterioration rate

| **Expression of confidence about the post-intervention deterioration rate relative to the current (observed) deterioration rate** | | | | |
|---|---|---|---|---|
| **Much lower** | **Lower** | **Same** | **Higher** | **Much higher** |
| | Medium | Highest | Lowest | |

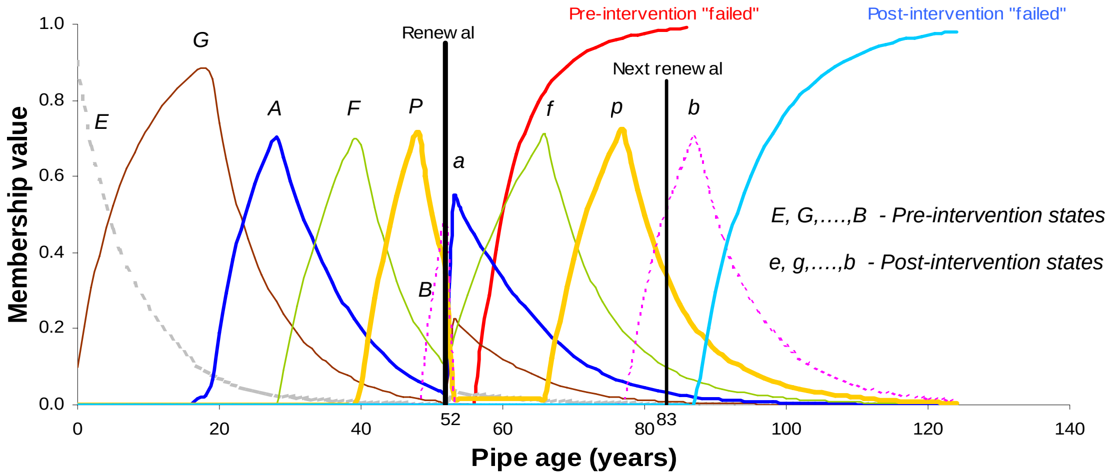


**Figure 3.** Deterioration curves before and after renewal (*E=Excellent, G=Good, A=Adequate, F=Fair, P=Poor, B=Bad*)

Once the condition improvement and the post-renewal deterioration rate matrices are established, a new fuzzy Markov-based deterioration process can be modeled, where the pipe continues to deteriorate from its post-renewal condition. If, for example, after renewal it takes 31 years for the pipe to deteriorate to a condition rating similar to its pre-renewal condition, as is illustrated in Figure 3, it can be said that the renewal action 'bought' 31 years of additional life.

## 3. Fuzzy Risk of Failure

The risk of failure is determined jointly by the likelihood (possibility) and the consequences of a failure. As stated earlier, failure of large-diameter transmission main is relatively a rare event and data on the consequences in terms of direct, indirect and social costs are difficult to come by. The fuzzy approach is therefore well suited to exploiting the qualitative understanding many practitioners have about the conditions that affect these costs. As the encoding process of failure consequences into fuzzy sets was beyond the scope of the underlying research, it was assumed that these consequences could be described as a 9-grade (*Extremely low, Very low, Quite low, Moderately low, Medium, Moderately severe, Quite severe, Very severe, Extremely severe*) possibility mass function.

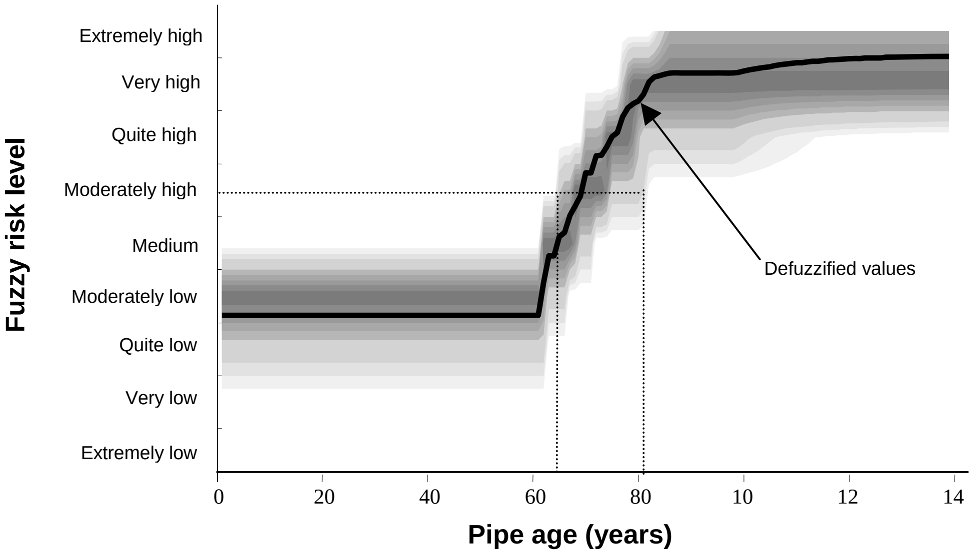


**Figure 3.** Life-time fuzzy risk

Using a set of fuzzy rules [7], the fuzzy consequence mass function is coupled with the mass function that defines the possibility of failure to obtain another mass function that describes the risk of failure as a 9-grade (*Extremely low*, *Very low, Quite low, Moderately low*, *Medium*, *Moderately high, Quite high*, *Very high*, *Extremely high*) fuzzy set. The risk mass function (or fuzzy number) is calculated for each time to obtain the fuzzy risk of failure throughout the life of the pipe. The result is a fuzzy risk curve as illustrated in Figure 3. The grey levels represent membership values to risk levels (darker grey for a higher membership).

## 4. Making Decisions

### *4.1. Expected Residual Life of Pipe*

Maximum risk tolerance (MRT) is used as a decision criterion. A water utility, through a consensus-building process like Delphi, will define the MRT, while considering both the possibility of failure and the failure consequences. Consequently, it can be said that, using a risk approach, MRT actually determines the expected residual life of the pipe. For example, in Figure 3, a MRT = *Moderately high* results in expected life of about 65 to 80 years, with a most likely value (MLV) of about 70 years (represented by the darkest grey level).

### *4.2. Maximum Risk Tolerance as a Decision Criterion*

It can be assumed that any decision to renew or rehabilitate a pipe segment or section will always be preceded by an inspection and condition assessment. Thus, if the deterioration model predicts that MRT is going to be reached at a given time, it follows that an inspection/condition assessment will be scheduled around that time [7]. This inspection/condition assessment can have one of the two outcomes:

- The observed condition of the pipe is better than predicted (the model overestimated the deterioration rate) and MRT has not yet been reached. In this case the deterioration model is re-calibrated to include the newly acquired data, then re-applied and the next inspection/condition assessment is scheduled for the next time at which MRT is predicted to be reached.
- The observed condition of the pipe is the same or worse than the model predicted and current risk is equal to or exceeds MRT. In this case renewal work has to be planned immediately and implemented as soon as possible.

With this approach, when pipe renewal is required it is often necessary to select the most appropriate among several alternative renewal technologies that are available in the market. In the selection, the user has to consider both the improvement that the renewal action will affect and the post renewal deterioration rate. The user may resort to the time 'bought' concept explained earlier to make this selection. If, for example, a renewal technology that costs $100,000 buys 20 years of additional life (i.e., postpones subsequent renewal by 20 years until the time at which MRT is reached again), the normalized cost of this technology can be thought of as $5,000 per year of extra life. The user will usually select the technology with the lowest cost per year of extra life.

### *4.3. Risk/Cost Trade-off as a Decision Criterion*

The decision approach described in Section 4.2 above is valid for cases where the cost of asset renewal is independent of the condition of the renewed asset. This approach also implies that once MRT is determined, the asset owner sees no value at all in operating the asset at risk levels that are below MRT. However, the cost of some renewal technologies can depend on the condition of the asset, i.e., the more deteriorated the pipe, the more expensive it is to renew. Further, asset owners may see value in operating the asset at risk levels below MRT. Kleiner [8] introduced a process to explore renewal strategies under these premises.

For each renewal strategy it is assumed that the more deteriorated the asset, the higher the cost to implement renewal. The expected cost of renewal is calculated based on a cost matrix, provided by the renewal technology vendor or by experts, and on the fuzzy condition rating of the asset.

In order to be able to compare renewal alternatives that may be scheduled at different points along the time line and/or have different effective longevities, it is assumed that a renewal alternative is applied over and over again in perpetuity. For example, at age $t$ an asset has a condition rating $x$. The asset is renewed and consequently its condition rating is improved to $y$. Subsequently the asset is allowed to deteriorate and it takes $T$ years for it to reach back to condition $x$. At this point it is renewed again and so on in perpetuity. As a first approximation, it is assumed that the renewal cycles are identical. Consequently, it is possible to compute the discounted cost of infinite renewal cycles, and because of this perpetuity, the discounted cost does not depend on the duration of the renewal cycle.

An additional feature of these renewal cycles is that the condition rating $x$ actually denotes the maximum risk to which the asset will be exposed throughout its life. This risk is represented of course by a fuzzy mass function (or number), as explained earlier.

Each *renewal strategy* will therefore have two calculated attributes, total discounted cost and the maximum failure risk level. Because cost and risk are non-commensurate in their units, they cannot be combined to arrive at a global optimum. Instead, they can be mapped on a Pareto-type chart and the decision maker can select the preferred strategy among the Pareto-efficient ones.

## 5. Example

The Arizona Public Service Company (APS) provided data on a 96" (2400 mm) prestressed concrete cylinder pipe (PCCP) installed in 1978, and inspected in 1997, 1999 and 2002. The 1997 inspection comprised a visual inspection (no spalling no cracks no stains) and an impulse echo test, which revealed very firm sound. The 1999 and 2002 inspections employed a proprietary NDE technology named remote field eddy current/ transformer coupling (RFEC/TC), which revealed 5 prestressing wire breaks in both inspections. Table 4 presents the condition ratings obtained after applying the fuzzy synthetic evaluation technique described earlier. Note that the condition rating post installation was assumed rather than deciphered.

**Table 4.** Example - condition ratings of 96" PCCP

| Year | Excellent | Good | Adequate | Fair | Poor | Bad | Failed |
|---|---|---|---|---|---|---|---|
| 1978 (installation) | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 |
| 1997 | 0.09 | 0.85 | 0.06 | 0 | 0 | 0 | 0 |
| 1999 | 0.06 | 0.85 | 0.09 | 0 | 0 | 0 | 0 |
| 2002 | 0.06 | 0.85 | 0.09 | 0 | 0 | 0 | 0 |

It can be seen that the first 19 years witnessed a relatively slow deterioration, while the subsequent 5 years showed very slow or no deterioration. Figure 4 illustrates the results of training the model on the condition ratings of all three inspections.

Suppose further that the fuzzy failure consequence is evaluated as Q*uite low* (0, 0, 1, 0, 0, 0, 0, 0, 0), and MRT of the pipe owner is rated *Medium*. The resulting fuzzy risk curve that is predicted for the life of the pipe is illustrated in Figure 5. The age at which MRT is expected to be reached is about 100 years (97 years is the conservative approach), therefore the next inspection should be scheduled to that year. In this example, at age 97 the condition rating of the pipe is predicted to be $C_{97}$ = (0, 0, 0, 0, 0.1, 0.3, 0.6).

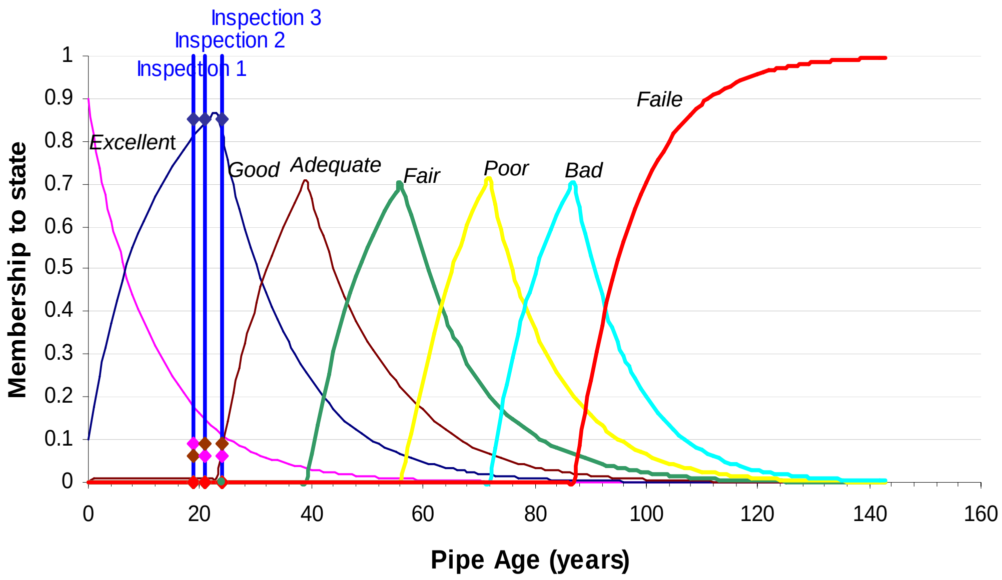


**Figure 4.** Example - trained deterioration model

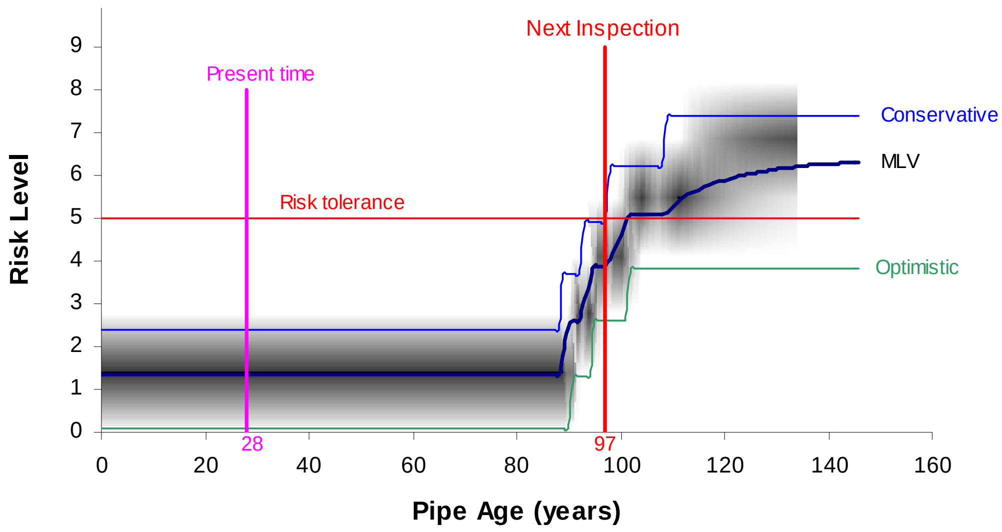


**Figure 5**. Example: fuzzy risk curve

If the decision criterion is only MRT, and if inspection reveals that the condition rating of the pipe is equals or worse that predicted, then renewal should be immediately scheduled. Otherwise the model should be re-calibrated and re-applied to obtain the next inspection timing (i.e., the time when MRT is expected to be reached according to the re-trained model). To select a renewal technology, use expert input to compute, for each alternative technology, the expected improvement in the condition rating of the pipe and the time it would take for the pipe to deteriorate back to $C_{97}$ rating. (i.e., time 'bought'). Choose the technology that provides the smallest ratio between cost and 'time bought' (i.e., the smallest cost per 'year bought').

When risk/cost trade-off is to be considered as a decision criterion, renewal strategies are considered and compared. Two such possible strategies are illustrated in Figure 6. Strategy 1 comprises a renewal technology that if applied at age 90, when $C_{90}$ = (0, 0, 0, 0, 0.2, 0.6, 0.2), will buy the pipe 40 years (i.e., 40 years after renewal the pipe will be back at $C_{90}$). As a first approximation, it is assumed that this technology is applied at years 90 + 40n (n=1, 2,…) in perpetuity. The discounted cost of this infinite series of renewals $S_1$ can be computed [8], and denoted $S_1$. The maximum risk to which the pipe is expected to be exposed with Strategy 1 is $R_1$ = (0, 0.1, 0.9, 0, 0, 0, 0, 0, 0) or 0.1 membership to *Very low*, 0.9 membership to *Quite low* and zero membership to all other risk levels. Similarly, strategy 2 is applied at $C_{96}$ = (0, 0, 0, 0, 0.1, 0.3, 0.6) and buys the pipe 21 years. The discounted cost of the infinite series at years 95 + 21n (n=1, 2,…) is $S_2$.and the maximum risk to which the asset is subjected is $R_2$ = (0, 0, 0, 0.1, 0.5, 0.4, 0, 0, 0).

It is clear that if $R_1 < R_2$ and $S_1 < S_2$ then alternative 1 is superior to alternative 2 (lower cost and smaller risk). However, if for example $R_1 < R_2$ and $S_1 > S_2$ then there is a clear trade-off between higher risk and lower cost. An added complexity is the fact that the risk magnitudes $R_i$ are fuzzy numbers. The simplest way to compare those is to defuzzify them, however, other techniques can be used, which are beyond the scope of this paper.

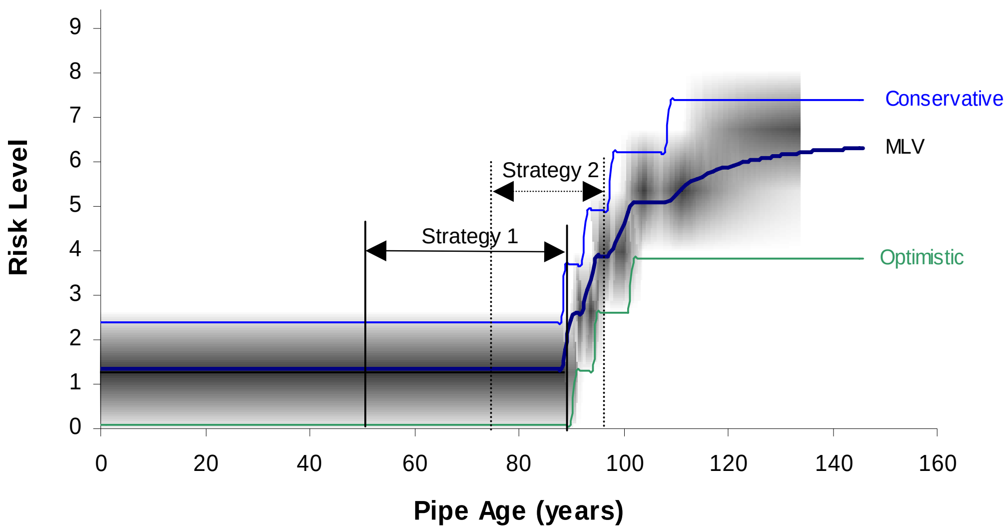


**Figure 6.** Example: Renewal strategies

When several renewal alternatives are to be considered, it is useful to plot those on a risk versus cost chart, in order to obtain the Pareto front of non-inferior alternatives (Figure 7). The decision as to which point on this Pareto front is the preferred strategy depends on the risk versus cost preference of the decision maker.

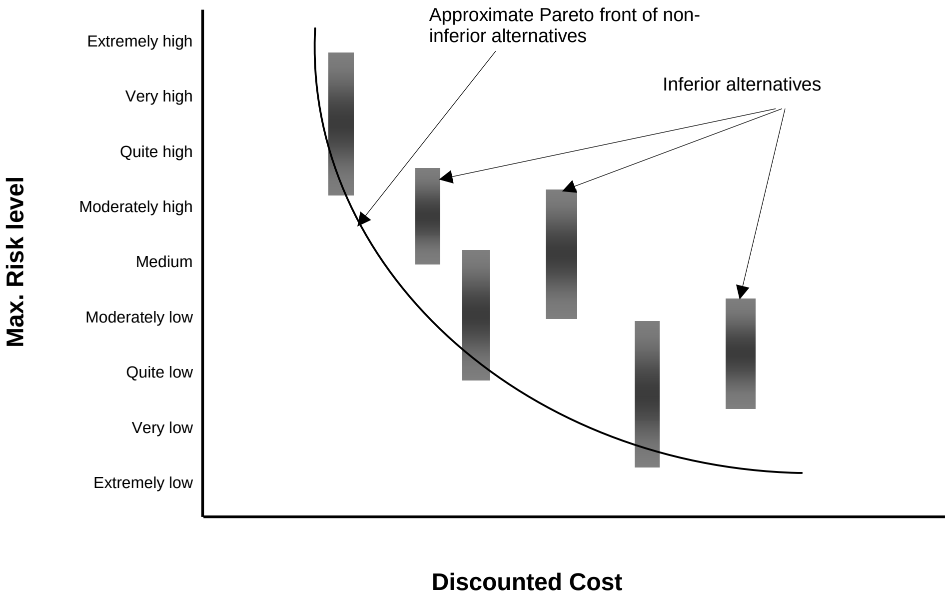


**Figure 7.** Example: Pareto front of non-inferior renewal alternatives

## 6. Summary

Fuzzy-based techniques are particularly suited to modeling the deterioration of buried infrastructure assets, for which data are scarce, cause-effect knowledge is imprecise and observations and criteria are often expressed in vague terms. An approach to manage the renewal of these assets was developed and in this paper is demonstrated with the help of an example. This approach can be summarized in these clearly defined steps:

1. Inspect the asset, record distress indicators and interpret them into a condition rating.
2. Use the condition rating to train a fuzzy Markov-based deterioration model and generate risk projection for the asset life.
3. Evaluate renewal strategies, including renewal technologies and scheduling alternatives. Decision criteria may include discounted costs of the strategies, the maximum risk to which they subject the asset and possibly the expected length of the renewal cycle.
4. If the deterioration model was trained using condition assessment data that are old, it is prudent to perform an inspection/condition assessment before the actual renewal is carried out. The new data will be used either to confirm the decision or to re-train the model for future analysis.

More data are needed to enable further research into various aspects of the approach and its ability to replicate the actual behaviour of large buried pipes.


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