Optimization of Hydraulic Steel Structure Inspection Intervals Using Reinforecment Learning _Part 1 - Overview

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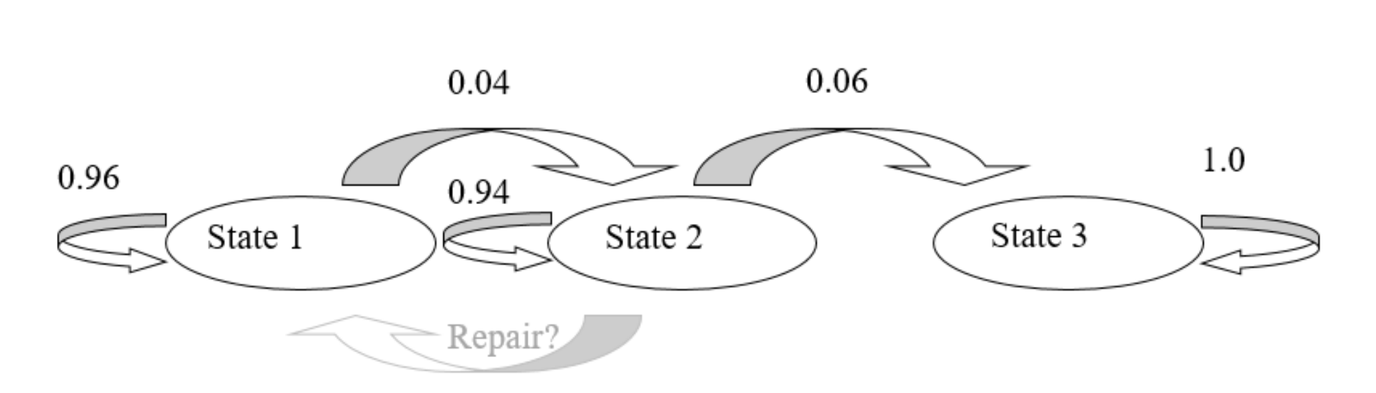
Introduction

This work explores the application of algorithms born in the reinforcement learning branch of artificial intelligence (AI) industry and applied to hydraulic steel structure asset management. Specifically, the use of a Partially Observable Markov Decision

Process applied to deterioration of radial (Tainter) gates on dams. The fundamentals of the problem include structural inspection, structural deterioration, maintenance activities, maintenance intervals, and condition states. Optimizing inspection intervals depends on much more than just the condition of the structure.

Markov Decision Process



Example three state Markov Chain with terminal condition state showing probabilities of transitioning from one state to another.

Current Radial Gate Inspection Practice

Owner/Regulator	Gate Inspection Interval: High and Medium Hazard	Gate Inspection Interval: Low Risk	Reference
Federal Energy Regulatory Commission	10 years	None	FERC Tainter Gate Initiative - Rev 1
United States Army Corps of Engineers	5 years	5 years	ER 1110-2-8157
United States Bureau of Reclamation	6 years (max)	6 years (max)	Reclamation Manual - Directives and Standards During Comprehensive and/or Periodic Facility Reviews (3 year)

Required Radial Gate Inspection Intervals

Example Element Level Rating System

Defects	Condition States 1 GOOD	2 FAIR	3 POOR	4 SEVERE
Corrosion (1000)	None.	Freckled rust. Corrosion of the steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge.
Cracking (1010)	None.	Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar.	Identified crack that is not arrested but does not warrant structural review.	

FHWA Element Level Inspection. Element 107 - Steel Open Girder/Beam.
Reference - FHWA Manual for Element Level Bridge Inspection

Radial Gate Rating System for Corrosion ERDC-ITL TR-09-4 | *6 Condition State*

No.	Description	Example
1	Little or no corrosion is present. The weathering steel is coated uniformly and remains in excellent condition. Oxide film is tightly adhered. The connectors (welds, rivets, etc.) are sound.	
2	Surface rust or surface pitting has formed or is forming. The weathering steel has not corroded beyond design limits. Oxide film has a dusty to granular texture.	
3	Steel has measurable section loss from corrosion but does not warrant structural analysis. Oxide film is flaking (1/2 in. in diameter). Rusting between plates is beginning to distress the connection. Minor swelling exists.	
4	Corrosion is advanced. Oxide film has a laminar texture with thin sheets of rust. Section loss is sufficient (<= 10% of the total cross-sectional area) to warrant structural analysis to ascertain the impact on the ultimate strength and/or serviceability of either the element or the HSS. Rusting between plates has caused serious distress to the connection. The plates may be badly distorted; however, all connectors (rivets/bolts) are still functioning.	
5	Corrosion has resulted in section loss (> 10% of the total cross-sectional area) and is sufficient to warrant structural analysis to ascertain the impact on the ultimate strength and/or serviceability of either the element or the structure. Rusting between plates has caused serious distress to the connection, which warrants analysis of the HSS to ascertain the impact on the serviceability of the HSS. Some rivets or other connectors may have popped or are no longer effective.	
6	Structural Failure	

Input Examples

Example Deterioration Matrix
3 Condition State

$$corrosion := \begin{pmatrix} CS_{1-1} & CS_{1-2} & CS_{1-3} \\ CS_{2-1} & CS_{2-2} & CS_{2-3} \\ CS_{3-1} & CS_{3-2} & CS_{3-3} \end{pmatrix} := \begin{pmatrix} 0.96 & 0.04 & 0.00 \\ 0.00 & 0.94 & 0.06 \\ 0.00 & 0.00 & 1.00 \end{pmatrix}$$

Example Rewards (Cost) Vector
3 Condition State

$$Reward := \begin{pmatrix} Cost\_of\_CleanPaint\_VisualInspectArmsReach\_When\_VeryGood\_Condition \\ Cost\_of\_CleanPaint\_VisualInspectArmsReach\_When\_ModerateSectionLoss\_Condition \\ Cost\_of\_CleanPaint\_VisualInspectArmsReach\_When\_Failed\_Condition \end{pmatrix} = \begin{pmatrix} -\$43k \\ -\$128k \\ -\$6{,}111k \end{pmatrix}$$

Example Observation Matrix
3 Condition State

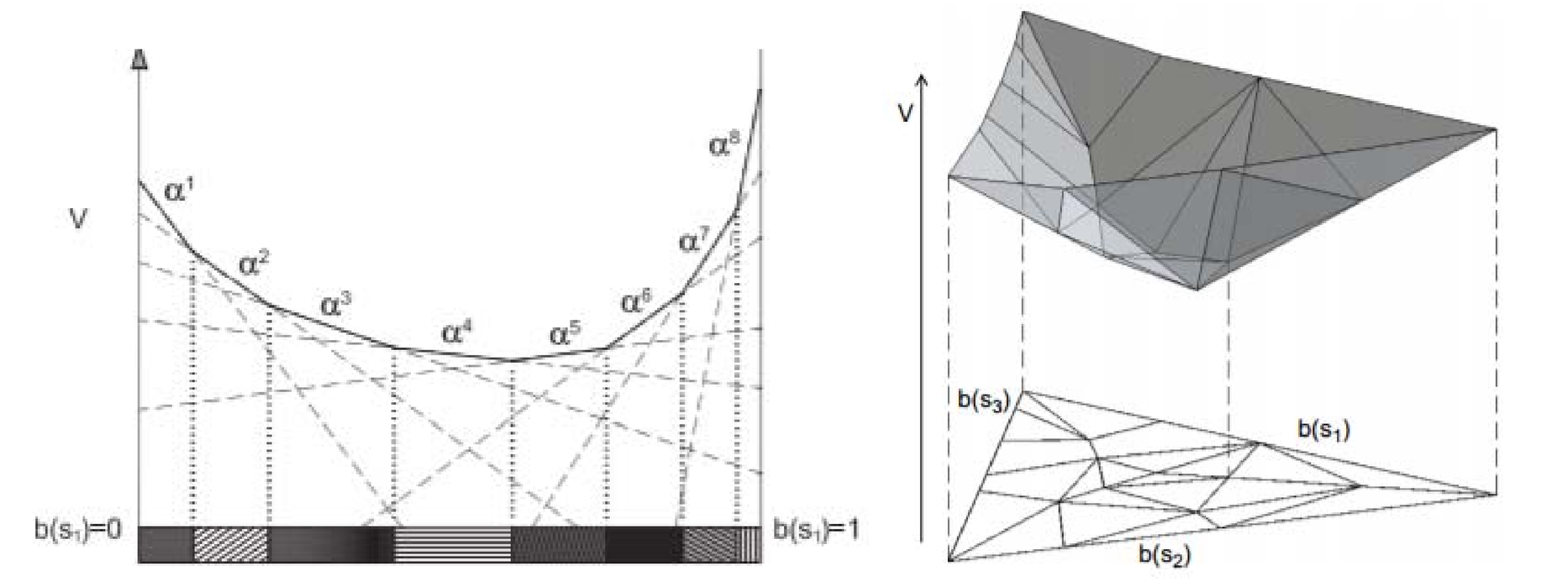
$$Observation := \begin{pmatrix} CS_{1-1} & CS_{1-2} & CS_{1-3} \\ CS_{2-1} & CS_{2-2} & CS_{2-3} \\ CS_{3-1} & CS_{3-2} & CS_{3-3} \end{pmatrix} = \begin{pmatrix} 0.69 & 0.26 & 0.05 \\ 0.14 & 0.69 & 0.17 \\ 0.00 & 0.14 & 1.0 \end{pmatrix}$$

POMDP Value Function

$$V^{*}(b) = max_{a\in A}\left[\sum_{s'\in S} b(S)\sum_{s'\in S} P(S'|S,a)r(S,a,S') + \gamma\left(\sum_{o\in O}\sum_{s'\in S} p(o|s',a)\sum_{s'\in s} P(S'|S,a)b(s)V^{*}(b(S'))\right)\right]$$

Mathematical Engine - Incorporating Bayesian Methods
Reference - Papakonstantinou 2014

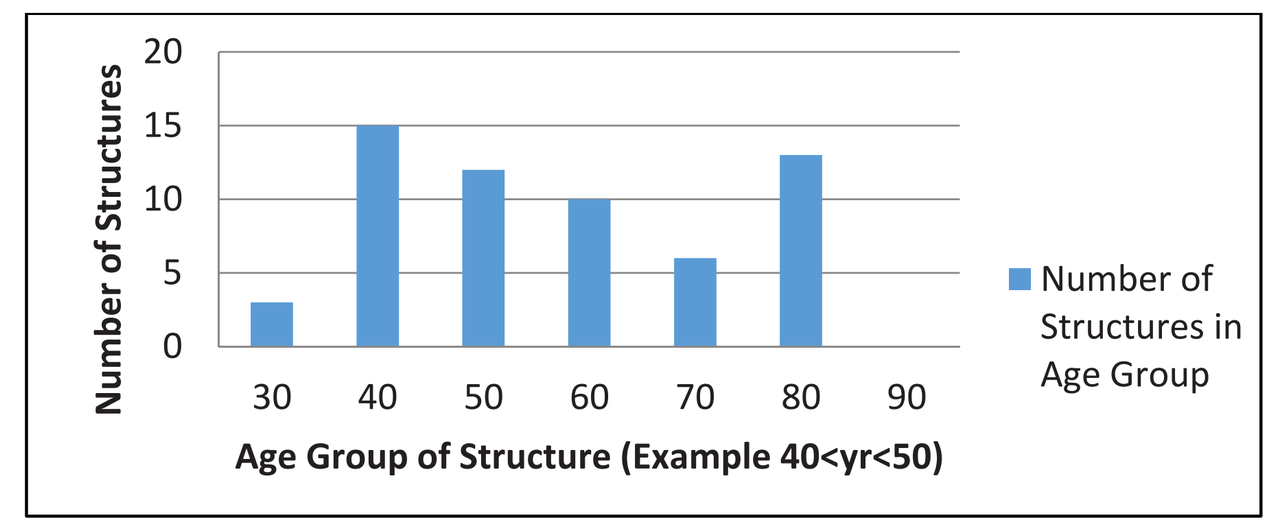
Two State and Three State Belief Simplex with a-vectors Plotted - Forming a Visual Representation of the Value Function



Visual Presentation of Value Funtion Output
Reference - Papakonstantinou 2014

Data Gathering & Analysis for Radial Gates

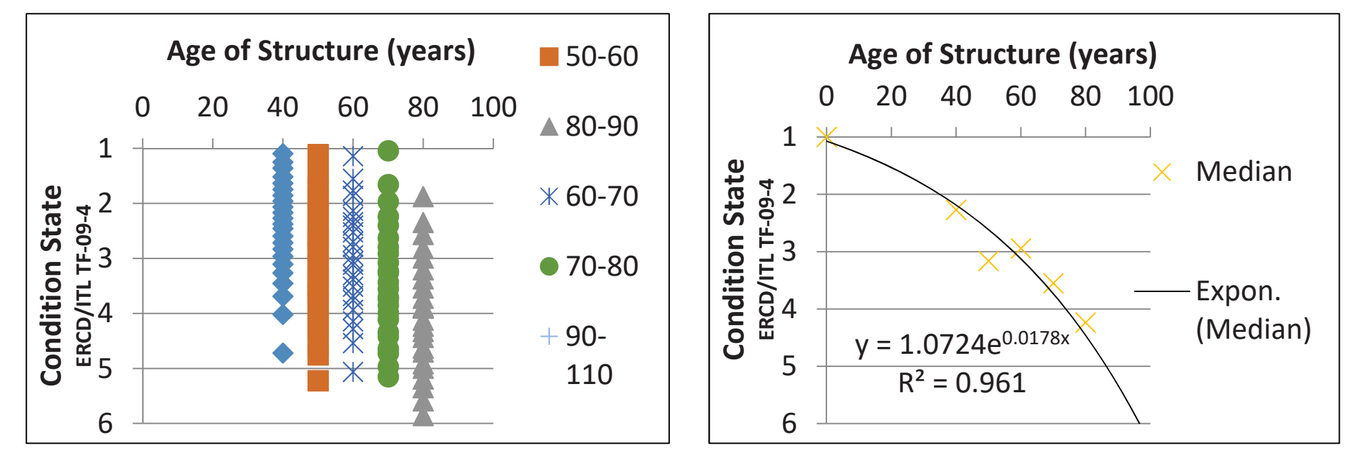
Number of Structures in Each Age Group Reported in Formsite Survey and Used in the Analysis.



Example Formsite Survey Results with all Dam Names Removed.

Name	# of Structures, Dimension and Type	Corrosion Condition State	Fatigue Condition State
LD	1, 15' high by 22' wide Radial Gates	Corrosion: 2	Fatigue: 2
LDR	1, 15' high by 22' wide Radial Gates	Corrosion: 1	Fatigue: 2
BF	4, 10' high x 20' wide Radial Gates	Corrosion: 2	Fatigue: 3

Deterioration Modeling



The deterioration models are used to calculate transition probabilities for each deterioration matrix. For the Radial Gate Model 6 condition states were used similar to ERDC-ITL-TR-09-4.

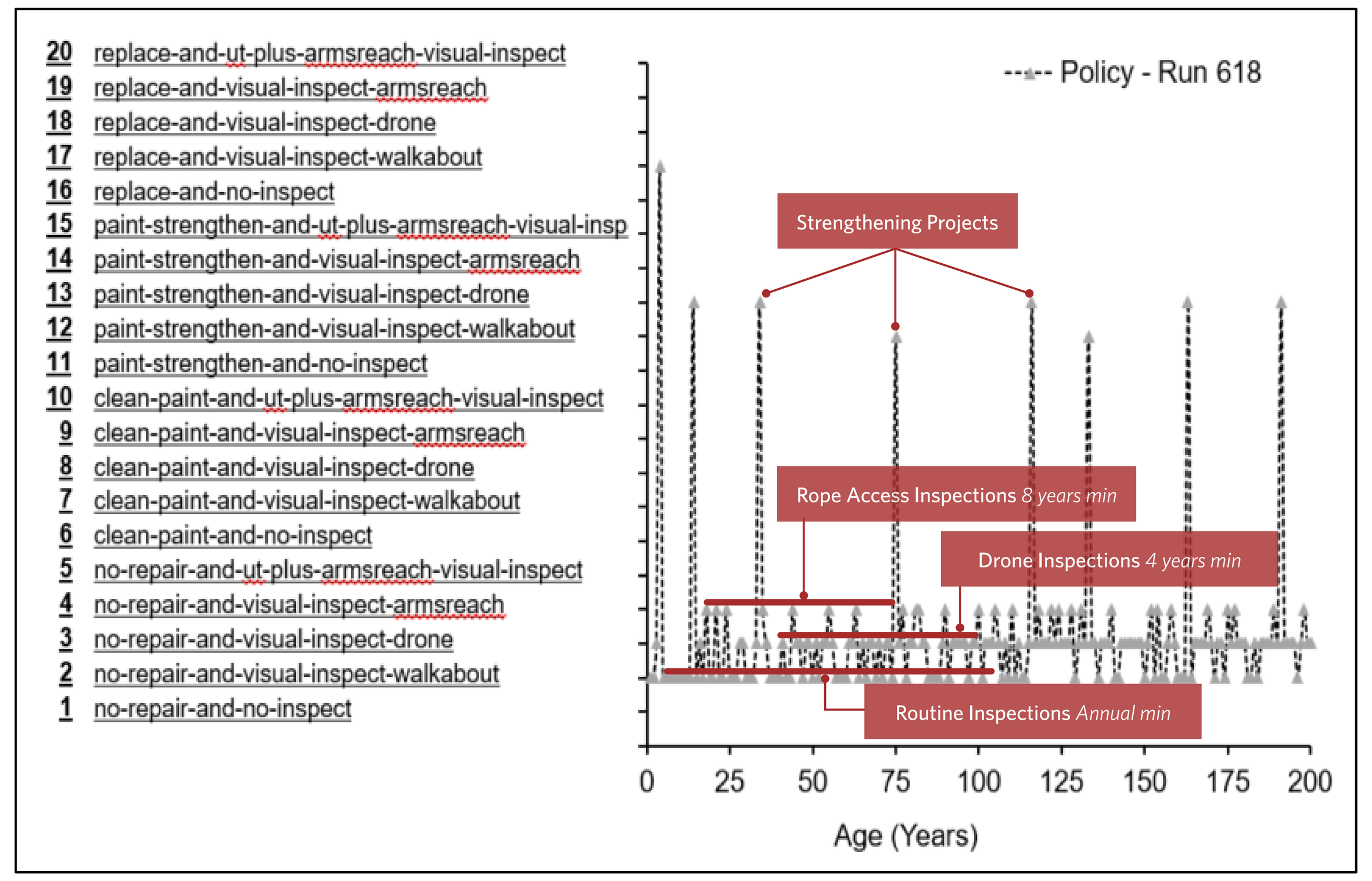
Results

Action Pair Summary Key

Action Pairs	No Repair	Clean-paint	Paint-strengthen	Replace
No Inspect	1	6	11	16
visual-inspect-walkabout	2	7	12	17
visual-inspect-drone	3	8	13	18
visual-inspect-armsreach	4	9	14	19
ut-plus-armsreach-visual-inspect	5	10	15	20

Increasing Cost

Spillway Gate Model Results - Estmate of Optimal Structure Management Policy



Findings

1. The deterioration on structures with private owners was faster compared to government due to maintenance and operational policies.
2. There is a spike in fatigue deterioration between 60 and 70 years old which corresponds with the advent of welding technology. A large percentage of the deterioration for fatigue/cracking on radial gates is related to tack weld cracking. It is difficult to decipher between a fatigue related tack weld crack and otherwise so the cracking was lumped into what would be more appropriately called “Fatigue and Cracking”.
3. Older-riveted hydraulic structures show less fatigue damage than welded structures.
4. The inspection costs per gate and per square foot of projected area varied depending on quantities. The more gates or structures to inspect the lower the cost per item.
5. More detailed inspections cost more but the benefit of a higher probability of detection can outweigh added cost. The model does not give up on better observation data even if it costs more.
6. The modeling showed that early rehabilitations on structures can help curb the deterioration model early. This is opposite from what many asset owners often do but if done early on the deterioration curve the structure benefits through its entire remaining life cycle vs. just the last few years. Early retrofit work pays off in the long run more than waiting.
7. The higher the cost of an activity the less likely the agent will choose it. If a failed condition state has a large negative value the agent will take actions that keep it away from the expensive place. The higher the cost the more conservative the agent will be in its avoidance.

For Further Details See:

USSD Publication: Optimization of Hydraulic Steel Structure Inspection Intervals Using Reinforcement Learning_Part 1 - Overview