Supplementary Materials

Innovative Framework for Cost-Effective and Reliable Networks via P-graph and Machine Learning in Water Infrastructure Management

Andres Castellar-Freile[1], Jean Pimentel[2*], Ákos Orosz[3], Brian Guillermo[1], Deanna Mariano[1], Heriberto Cabezas[4], Ferenc Friedler[2], Kirti M. Yenkie[1*]

[1]Department of Chemical Engineering, Rowan University, Glassboro, 08028, New Jersey, US
[2]Department of Systems Science, Széchenyi István University, Egyetem tér 1, Győr, H-9026, Hungary
[3]Department of Computer Science and Systems Technology, University of Pannonia, Egyetem u. 10, Veszprém, H-8200, Hungary
[4]Department of Applied Sustainability, Széchenyi István University, Egyetem tér 1, Győr, H-9026, Hungary

*Corresponding authors
e-mail address: yenkie@rowan.edu (K. M. Yenkie)
e-mail address: pimentel.losada.jeanpierre.andres@sze.hu (J. Pimentel)

S.1. Hyperparameters for Machine Learning Models

The hyperparameters used for the Machine Learning (ML) models were determined through hyperparameter tuning using cross-validation to improve prediction accuracy and avoid overfitting. The final selected parameters are presented in Table S1.

Table S1. Hyperparameters used for training the machine learning models applied to predict the pipeline failure rate

Model	Hyperparameter	Value	Description
Extreme Gradient Boosting (XGBoost)	Subsample	0.6	Fraction of training samples used per iteration
	Number of Estimators	40	Number of boosting trees used in the model
	Maximum Depth	5	Maximum depth of individual trees
	Learning Rate	0.1	Step size used to update model weights
	Column Sample by Tree	0.8	Fraction of features used for building each tree
	Number of Iterations	100	Number of boosting rounds used during training
	Objective	Squared Error	Regression objective minimizing squared error
	Cross-validation Number	10	Number of folds used for cross-validation
Neural Networks	Neurons 1	8	Neurons of the first hidden layer
	Neurons 2	32	Neurons of the second hidden layer
	Dropout Rate	0.05	Fraction of neurons randomly deactivated during training
	L2 Lambda	0.0001	Ridge regression (regularization function)
	Batch Size	16	Number of samples processed per training batch
	Epochs	200	Total training iterations over the dataset
	Activation Function 1	ReLu	Activation function of the first hidden layer
	Activation Function 2	ReLu	Activation function of the second hidden layer
	Activation Function 3	Sigmoid	Activation function of the outer layer
	Loss	MSE	Regression objective minimizing squared error
	Learning rate	0.001	Step size used for weight updates

S.2. Complete set of input features used for the machine learning model

Tables S2 and S3 show the complete set of input features used for the ML-based reliability prediction of pipeline segments. The pipe material and flow type variables were transformed into numerical values using label-encoding.

For pipe material, there are eight main types: High-Density Polyethylene (HDPE) encoded as 1, Ductile Iron Pipe (DIP) encoded as 2, Steel pipe encoded as 3, Polyvinyl Chloride (PVC) encoded as 4, Thermoplastic Composite Pipe (TCP) encoded as 5, Reinforced Concrete Pipe (RCP) encoded as 6, Vitrified Concrete Pipe (VCP) encoded as 7, and Asbestos Cement Pipe (ACP) encoded as 8.

Flow type was encoded as follows: flow by gravity (0), and flow by force (1). Additionally, the *Years Since Last Inspection* were calculated using 2024 as the current year.

Table S2. Complete set of input features used for the ML model (part 1)

Pipe #	Segment Start	Segment End	Remaining Life [Years]	Pipe Size [in]	Pipe Material	Segment Length [km]
1	WWTP	2	30	41.77	6	0.114
2	2	PS-3	45	33.19	3	1.391
3	PS-3	4	60	35.80	6	0.837
4	4	5	30	33.59	6	1.055
5	5	PS-6	41	38.58	2	1.663
6	PS-6	7	30	45.75	1	0.456
7	7	8	30	38.99	6	0.976
8	8	9	45	41.48	5	0.752
9	9	10	41	40.45	2	0.895
10	10	11	30	32.65	1	0.889
11	11	12	45	30.56	5	1.129
12	12	PS-13	62	24.54	3	3.405
13	10	14	30	16.72	6	0.725
14	14	PS-15	30	15.42	1	0.560
15	PS-15	16	30	12.67	1	0.557
16	17	16	45	17.06	3	2.780
17	17	18	60	18.31	3	1.984
18	18	19	30	22.45	1	0.832
19	19	PS-3	41	25.00	2	0.393
20	PS-3	20	45	34.30	5	1.949
21	20	21	55	21.25	6	1.300
22	21	PS-22	45	9.66	3	0.495
23	20	PS-23	41	36.32	2	3.045
24	PS-23	24	53	34.66	6	1.138
25	24	25	30	35.31	1	1.113
26	26	25	45	19.71	5	0.739
27	PS-27	26	45	11.03	3	0.270
28	16	PS-27	41	12.39	2	0.848
29	PS-23	28	30	13.81	6	1.539
30	28	29	53	13.30	1	1.840
31	29	PS-30	30	13.01	1	1.632
32	PS-30	31	30	12.34	1	0.152
33	32	31	30	15.53	1	0.760
34	25	32	45	17.47	3	0.868
35	PS-3	WWTP	75	41.77	6	1.505
36	PS-22	WWTP	75	9.66	6	5.250
37	PS-6	PS-3	75	38.58	6	3.554
38	PS-6	7	75	45.75	6	0.456
39	7	8	75	38.99	6	0.976

40	10	8	75	32.65	6	1.647
41	PS-13	10	75	40.45	6	5.423
42	PS-3	20	75	34.30	6	1.949

Table S3. Complete set of input features used for the ML model (part 2)

Pipe #	Years Since Last Inspection	Original Installation [Year]	Population Density [ppsqmi]	Flow Type	Flow Rate [MGD]	Distance from WWTP [km]
1	45	1980	10.38	0	21.15	0.114
2	30	1995	10.38	1	21.15	1.505
3	15	1980	10.38	0	8.64	2.342
4	45	1980	10.38	0	8.64	3.397
5	34	1991	10.38	1	8.64	5.060
6	45	1980	10.38	0	8.64	5.515
7	45	1980	10.38	0	8.64	6.491
8	30	1995	1797.42	0	8.64	7.243
9	34	1991	1797.42	0	8.64	8.138
10	45	1980	1797.42	0	6.16	9.027
11	30	1995	1797.42	0	6.16	10.156
12	13	1995	1797.42	1	6.16	13.561
13	45	1980	1797.42	0	2.49	8.863
14	45	1980	1208.29	1	2.49	9.423
15	45	1980	1208.29	1	0.03	8.051
16	30	1995	2621.02	0	3.39	7.494
17	15	1995	2621.02	0	3.39	4.714
18	45	1980	2621.02	0	3.39	2.730
19	34	1991	2621.02	0	3.39	1.899
20	30	1995	3625.13	0	9.11	3.454
21	20	1980	3625.13	0	1.91	4.755
22	30	1995	3625.13	0	1.91	5.250
23	34	1991	3625.13	1	7.20	6.500
24	22	1980	3625.13	0	6.18	7.637
25	45	1980	1691.11	0	6.18	8.750
26	30	1995	1691.11	0	2.83	9.490
27	30	1995	1691.11	1	2.83	9.760
28	34	1991	1691.11	1	3.36	8.342
29	45	1980	3625.13	0	1.02	8.039
30	22	1980	3625.13	0	1.02	9.879
31	45	1980	424.71	1	1.02	11.511
32	45	1980	424.71	1	3.35	10.531
33	45	1980	424.71	0	3.35	10.379
34	30	1995	424.71	0	3.35	9.619
35	0	2025	10.38	1	21.15	1.505
36	0	2025	3625.13	1	1.91	5.250
37	0	2025	10.38	1	8.64	5.060
38	0	2025	10.38	0	8.64	5.515
39	0	2025	10.38	0	8.64	6.491
40	0	2025	1797.42	0	8.64	8.138
41	0	2025	1797.42	1	6.16	13.561
42	0	2025	3625.13	0	9.11	3.454

S.3. Design and cost calculations for pipelines and storage tanks

The design and cost calculations for pipelines in the proposed case study are shown in Tables S4 and S5, respectively. To obtain the maximum flow rate, we used the maximum allowed velocity for pipeline segments in the pumps' suction and discharge. The prices were updated using the Chemical Engineering Plant Cost Index (CEPCI) for 2024 and 2022, whose values are 798.8 and 816, respectively [1]. The prices were obtained from AmeriTex Pipe & Products LLC for RCP material [2].

Table S4. Design calculations for pipelines in the proposed wastewater transportation case study

Pipe #	Pipe Diameter [in]	Pipe Length [km]	Flow Rate [m^3/h]	Flow Area [m^2]	Velocity [m/s]	Maximum Velocity [m/s]	Max Flow Rate [m^3/h]
1	41.77	0.11	3335	0.88	1.05	7.6	24187
2	33.19	1.39	3335	0.56	1.66	7.6	15274
3	35.80	0.84	1364	0.65	0.58	7.6	17771
4	33.59	1.06	1364	0.57	0.66	7.6	15643
5	38.58	1.66	1364	0.75	0.50	7.6	20631
6	45.75	0.46	1364	1.06	0.36	1.2	4583
7	38.99	0.98	1364	0.77	0.49	7.6	21081
8	41.48	0.75	1364	0.87	0.43	7.6	23850
9	40.45	0.90	1364	0.83	0.46	7.6	22687
10	32.65	0.89	971	0.54	0.50	7.6	14781
11	30.56	1.13	971	0.47	0.57	7.6	12944
12	24.54	3.41	971	0.31	0.88	7.6	8347
13	16.72	0.72	393	0.14	0.77	7.6	3875
14	15.42	0.56	393	0.12	0.91	7.6	3296
15	12.67	0.56	5	0.08	0.02	7.6	2225
16	17.06	2.78	535	0.15	1.01	7.6	4037
17	18.31	1.98	535	0.17	0.88	7.6	4646
18	22.45	0.83	535	0.26	0.58	7.6	6986
19	25.00	0.39	535	0.32	0.47	7.6	8668
20	34.30	1.95	1437	0.60	0.67	1.2	2576
21	21.25	1.30	301	0.23	0.37	7.6	6261
22	9.66	0.50	301	0.05	1.77	7.6	1293
23	36.32	3.05	1136	0.67	0.47	7.6	18290
24	34.66	1.14	975	0.61	0.44	7.6	16656
25	35.31	1.11	975	0.63	0.43	7.6	17288
26	19.71	0.74	446	0.20	0.63	7.6	5385
27	11.03	0.27	446	0.06	2.01	7.6	1687
28	12.39	0.85	531	0.08	1.89	7.6	2130
29	13.81	1.54	161	0.10	0.46	1.2	418
30	13.30	1.84	161	0.09	0.50	7.6	2451
31	13.01	1.63	161	0.09	0.52	7.6	2347
32	12.34	0.15	529	0.08	1.90	7.6	2112
33	15.53	0.76	529	0.12	1.20	7.6	3344
34	17.47	0.87	529	0.15	0.95	7.6	4233
35	41.77	1.51	3335	0.88	1.05	7.6	24187
36	9.66	5.25	301	0.05	1.77	7.6	1293
37	38.58	3.55	1364	0.75	0.50	7.6	20631
38	45.75	0.46	1364	1.06	0.36	7.6	29021
39	38.99	0.98	1364	0.77	0.49	7.6	21081
40	32.65	1.65	1364	0.54	0.70	7.6	14781
41	40.45	5.42	971	0.83	0.33	7.6	22687
42	34.30	1.95	1437	0.60	0.67	7.6	16312

Table S5. Cost calculations for pipelines in the proposed wastewater transportation case study

Pipe #	Cost 2022 [USD/ft]	Cost 2022 [USD]	Cost 2024 [USD]	Annualized Cost [USD/y]
1	0	$ -	$ -	$ -
2	0	$ -	$ -	$ -
3	0	$ -	$ -	$ -
4	0	$ -	$ -	$ -
5	0	$ -	$ -	$ -
6	0	$ -	$ -	$ -
7	0	$ -	$ -	$ -
8	0	$ -	$ -	$ -
9	0	$ -	$ -	$ -
10	0	$ -	$ -	$ -
11	0	$ -	$ -	$ -
12	0	$ -	$ -	$ -
13	0	$ -	$ -	$ -
14	0	$ -	$ -	$ -
15	0	$ -	$ -	$ -
16	0	$ -	$ -	$ -
17	0	$ -	$ -	$ -
18	0	$ -	$ -	$ -
19	0	$ -	$ -	$ -
20	0	$ -	$ -	$ -
21	0	$ -	$ -	$ -
22	0	$ -	$ -	$ -
23	0	$ -	$ -	$ -
24	0	$ -	$ -	$ -
25	0	$ -	$ -	$ -
26	0	$ -	$ -	$ -
27	0	$ -	$ -	$ -
28	0	$ -	$ -	$ -
29	0	$ -	$ -	$ -
30	0	$ -	$ -	$ -
31	0	$ -	$ -	$ -
32	0	$ -	$ -	$ -
33	0	$ -	$ -	$ -
34	0	$ -	$ -	$ -
35	$ 3,714.08	$ 18,343,603.18	$ 17,956,948.80	$ 2,154,859.66
36	$ 825.92	$ 14,226,223.44	$ 13,926,356.96	$ 1,671,182.84
37	$ 3,219.35	$ 37,541,116.90	$ 36,749,809.05	$ 4,410,029.89
38	$ 4,481.75	$ 6,698,370.70	$ 6,557,179.55	$ 786,870.97
39	$ 3,284.18	$ 10,514,571.61	$ 10,292,940.94	$ 1,235,167.70
40	$ 2,535.37	$ 13,701,256.86	$ 13,412,455.86	$ 1,609,513.97
41	$ 3,510.20	$ 62,453,245.64	$ 61,136,829.19	$ 7,336,507.34
42	$ 2,675.58	$ 17,108,925.49	$ 16,748,296.18	$ 2,009,819.60

The design and cost calculations for storage tanks in the proposed case study are shown in Tables S6 and S7, respectively. The number of tanks was calculated using a standard tank capacity of 1,000,000 gallons with a 66 ft diameter and 40 ft height obtained from CST Industries [3]. The cost for this tank was obtained from Matches [4] and was updated using the CEPCI values for 2014 and 2024 [1].

Table S6. Design calculations for storage tanks in the proposed wastewater transportation case study

Place	Flow Rate [m^3/h]	Flow in each point [m^3]	Required Storage Volume [m^3]	Total Tanks	Standard Volume [m^3]
Region A	301	7217	7217	2	7572
Region B	690	16556	16556	5	18930
Region C	977	23440	23440	7	26502
Region D	397	9536	9536	3	11358
Region E	971	23300	23300	7	26502
Total	3335	80049	80049	24	90864

Table S7. Cost calculations for storage tanks in the proposed wastewater transportation case study

Place	Cost 2014 [USD]	Cost 2024 [USD]	Total Cost (with installation) [USD]	Annualized Cost [USD/y]
Region A	$ 427,000.00	$ 592,063.18	$ 1,420,951.64	$ 190,235.27
Region B	$ 1,067,500.00	$ 1,480,157.96	$ 3,552,379.10	$ 475,588.18
Region C	$ 1,494,500.00	$ 2,072,221.14	$ 4,973,330.74	$ 665,823.45
Region D	$ 640,500.00	$ 888,094.78	$ 2,131,427.46	$ 285,352.91
Region E	$ 1,494,500.00	$ 2,072,221.14	$ 4,973,330.74	$ 665,823.45
Total	$ 5,124,000.00	$ 7,104,758.20	$ 17,051,419.68	$ 2,282,823.27

S.4. Sensitivity Analysis for Simultaneous Failures in the P-graph Framework

A sensitivity analysis was conducted to evaluate the impact of the number of simultaneous failures considered in the reliability assessment of the case study proposed for the wastewater transportation network. The analysis examines both the deviation (i.e. upper reliability bound – lower reliability bound/average reliability) in the estimated reliability values and the computational time required to evaluate all feasible configurations (2,048 network alternatives). All runs were performed using an Intel® Core i5 (11th generation) processor with 8 GB RAM. Fig. S1 presents the deviation in the estimated reliability values as a function of the maximum number of simultaneous failures considered, while Table S8 illustrates the corresponding computational time required for the reliability evaluation.

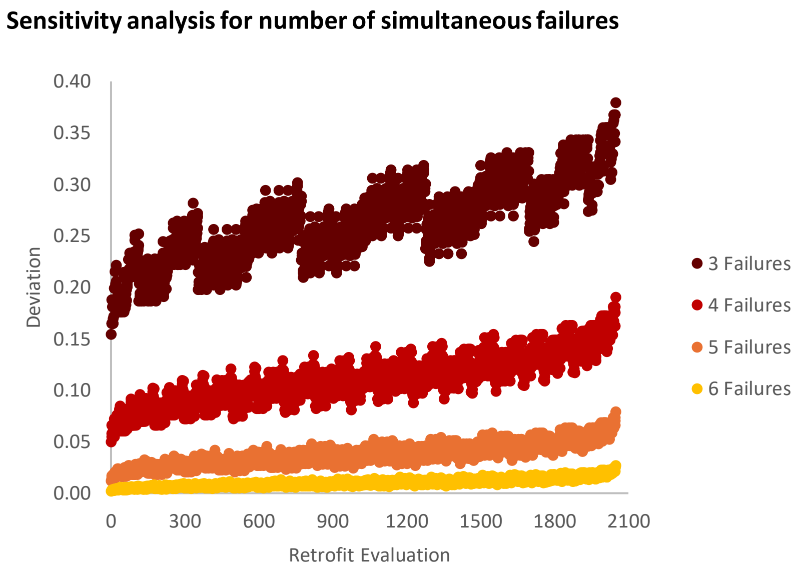

Fig. S1 Sensitivity analysis showing the deviation in the estimated reliability values for different limits on the number of simultaneous failures considered in the P-graph reliability evaluation

When only three simultaneous failures are included, the deviation can exceed 0.30 for some retrofit configurations, indicating a significant overestimation of reliability. Increasing the limit to four failures substantially reduces the deviation, while considering five failures further improves the accuracy, with deviations generally remaining below approximately 0.07. When six simultaneous failures are included, the deviation becomes very small, typically remaining below 0.03.

Table S8. Sensitivity analysis of the computational running time required for the reliability evaluation as a function of the number of simultaneous failures considered in the P-graph framework

Simultaneous Failures	Time [s]	Time [h]
3	1,001	0.28
4	4,459	1.24
5	33,805	9.39
6	135,314	37.59

While increasing the number of simultaneous failures improves the accuracy of the reliability estimation, it also significantly increases the computational effort required for the evaluation. As shown in Table S8, the computational running time for the entire set of designs grows rapidly with the number of simultaneous failures considered. The running time increases from approximately 0.28 hours when three failures are considered to 1.24 hours for four failures and 9.39 hours for five failures. When six simultaneous failures are evaluated, the running time rises dramatically to approximately 37.59 hours.

Taken together, these results highlight the trade-off between reliability estimation accuracy and computational efficiency. Based on this analysis, limiting the reliability evaluation to five simultaneous failures provides a practical balance between acceptable accuracy and manageable computational effort.

S.5. Results of the sensitivity analysis for adding storage tanks

The Pareto set results for varying the storage tank capacity at 100%, 75%, 50%, and 25% are shown in Tables S9, S10, S11, and S12, respectively.

Table S9. Pareto set for 100% storage tank capacity

N	Reliability Minimum	Reliability Maximum	Cost [10^6 USD/y]	Ext
1995	0.923	0.982	$ 23.32	'{'T3', 'P_37', 'P_42', 'T5', 'T4', 'P_41', 'P_35', 'P_38', 'T2'}'
1886	0.926	0.977	$ 21.31	'{'T3', 'P_37', 'T5', 'T4', 'P_41', 'P_35', 'P_38', 'T2'}'
1835	0.928	0.974	$ 15.99	'{'T3', 'P_37', 'P_42', 'T5', 'T4', 'P_35', 'P_38', 'T2'}'
1575	0.929	0.969	$ 13.98	'{'T3', 'P_37', 'T5', 'T4', 'P_35', 'P_38', 'T2'}'
1499	0.930	0.967	$ 10.67	'{'T3', 'P_37', 'P_42', 'T5', 'T4', 'P_35', 'T2'}'
1093	0.930	0.962	$ 8.66	'{'T3', 'P_37', 'T5', 'T4', 'P_35', 'T2'}'
1163	0.930	0.960	$ 6.26	'{'T3', 'P_42', 'T5', 'T4', 'P_35', 'T2'}'
715	0.929	0.954	$ 4.25	'{'T3', 'T5', 'T4', 'P_35', 'T2'}'
651	0.925	0.950	$ 4.10	'{'T3', 'P_42', 'T5', 'T4', 'T2'}'
301	0.923	0.944	$ 2.09	'{'T2', 'T5', 'T3', 'T4'}'
310	0.750	0.771	$ 2.00	'{'T1', 'T5', 'T3', 'T2'}'
90	0.750	0.769	$ 1.81	'{'T5', 'T3', 'T2'}'
500	0.738	0.759	$ 1.62	'{'T1', 'T5', 'T2', 'T4'}'
181	0.739	0.757	$ 1.43	'{'T5', 'T2', 'T4'}'
190	0.668	0.687	$ 1.33	'{'T1', 'T5', 'T2'}'
45	0.668	0.685	$ 1.14	'{'T5', 'T2'}'
39	0.556	0.572	$ 0.95	'{'T5', 'T4'}'
41	0.500	0.516	$ 0.86	'{'T1', 'T5'}'
4	0.492	0.506	$ 0.67	'{'T5'}'
11	0.388	0.403	$ 0.48	'{'T2'}'
5	0.301	0.315	$ 0.29	'{'T4'}'
7	0.295	0.309	$ 0.19	'{'T1'}'
0	0.290	0.303	$ -	'set()'

Table S10. Pareto set for 75% storage tank capacity

N	Reliability Minimum	Reliability Maximum	Cost [10^6 USD/y]	Ext
2039	0.905	0.968	$ 22.94	{'T1', 'P_41', 'P_37', 'T3', 'P_35', 'P_42', 'T4', 'T5', 'P_38', 'T2'}'
2045	0.899	0.963	$ 19.07	'{'T1', 'P_37', 'T3', 'P_35', 'P_42', 'T4', 'P_36', 'T5', 'P_38', 'T2'}'
2020	0.904	0.954	$ 15.60	'{'T1', 'P_37', 'T3', 'P_35', 'P_42', 'T4', 'T5', 'P_38', 'T2'}'
2018	0.897	0.949	$ 13.75	'{'T1', 'P_37', 'T3', 'P_35', 'P_42', 'T4', 'P_36', 'T5', 'T2'}'
1973	0.892	0.941	$ 13.66	'{'P_37', 'T3', 'P_35', 'P_42', 'T4', 'P_36', 'T5', 'T2'}'
1904	0.895	0.935	$ 10.29	'{'T1', 'P_37', 'T3', 'P_35', 'P_42', 'T4', 'T5', 'T2'}'
1929	0.892	0.934	$ 9.34	'{'T1', 'T3', 'P_35', 'P_42', 'T4', 'P_36', 'T5', 'T2'}'
1809	0.886	0.925	$ 9.25	'{'T3', 'P_35', 'P_42', 'T4', 'P_36', 'T5', 'T2'}'
1672	0.883	0.916	$ 5.88	'{'T1', 'T3', 'P_35', 'P_42', 'T4', 'T5', 'T2'}'
1462	0.844	0.873	$ 5.78	'{'T3', 'P_35', 'P_42', 'T4', 'T5', 'T2'}'
1234	0.838	0.865	$ 3.87	'{'T1', 'T3', 'P_35', 'T4', 'T5', 'T2'}'
1244	0.822	0.850	$ 3.72	'{'T1', 'T3', 'P_42', 'T4', 'T5', 'T2'}'
992	0.785	0.810	$ 3.63	'{'T3', 'P_42', 'T4', 'T5', 'T2'}'
731	0.779	0.802	$ 1.71	'{'T1', 'T3', 'T4', 'T5', 'T2'}'
315	0.703	0.724	$ 1.52	'{'T5', 'T3', 'T1', 'T2'}'
346	0.692	0.713	$ 1.14	'{'T5', 'T1', 'T2', 'T4'}'
226	0.629	0.648	$ 1.05	'{'T5', 'T4', 'T2'}'
110	0.629	0.648	$ 0.95	'{'T5', 'T1', 'T2'}'

65	0.568	0.584	$ 0.86	'{'T5', 'T2'}'
103	0.514	0.533	$ 0.76	'{'T5', 'T1', 'T4'}'
58	0.495	0.512	$ 0.67	'{'T5', 'T4'}'
19	0.461	0.477	$ 0.57	'{'T5', 'T1'}'
9	0.443	0.457	$ 0.48	'{'T5'}'
11	0.346	0.360	$ 0.38	'{'T2'}'
17	0.300	0.316	$ 0.29	'{'T1', 'T4'}'
7	0.299	0.313	$ 0.19	'{'T4'}'
1	0.290	0.305	$ 0.10	'{'T1'}'
0	0.290	0.303	$ -	'set()'

Table S11. Pareto set for 50% storage tank capacity

N	Reliability Minimum	Reliability Maximum	Cost [10^6 USD/y]	Ext
2042	0.744	0.818	$ 25.46	'{'P_35', 'T5', 'P_37', 'P_36', 'T1', 'P_38', 'P_41', 'T4', 'P_42', 'T2'}'
2023	0.746	0.815	$ 25.17	'{'P_35', 'P_37', 'P_36', 'T1', 'P_38', 'P_41', 'T4', 'P_42', 'T2'}'
1927	0.749	0.812	$ 25.08	'{'P_35', 'P_37', 'P_36', 'P_38', 'P_41', 'T4', 'P_42', 'T2'}'
2041	0.734	0.797	$ 22.37	'{'P_35', 'T5', 'P_37', 'T1', 'T3', 'P_38', 'P_41', 'T4', 'P_42', 'T2'}'
2001	0.736	0.795	$ 21.99	'{'P_35', 'T5', 'P_37', 'T1', 'P_38', 'P_41', 'T4', 'P_42', 'T2'}'
1920	0.738	0.792	$ 21.70	'{'P_35', 'P_37', 'T1', 'P_38', 'P_41', 'T4', 'P_42', 'T2'}'
1667	0.739	0.789	$ 21.61	'{'P_35', 'P_37', 'P_38', 'P_41', 'T4', 'P_42', 'T2'}'
1217	0.721	0.767	$ 21.51	'{'P_35', 'P_37', 'P_38', 'P_41', 'P_42', 'T2'}'
2031	0.684	0.741	$ 20.22	'{'T5', 'P_37', 'T1', 'P_38', 'T3', 'P_41', 'T4', 'P_42', 'T2'}'
1956	0.686	0.738	$ 19.84	'{'T5', 'P_37', 'T1', 'P_38', 'P_41', 'T4', 'P_42', 'T2'}'
1800	0.687	0.735	$ 19.55	'{'P_37', 'T1', 'P_38', 'P_41', 'T4', 'P_42', 'T2'}'
1457	0.688	0.732	$ 19.45	'{'P_37', 'P_38', 'P_41', 'T4', 'P_42', 'T2'}'
965	0.671	0.712	$ 19.36	'{'P_37', 'P_38', 'P_41', 'P_42', 'T2'}'
1995	0.632	0.684	$ 17.05	'{'P_35', 'T5', 'P_37', 'T1', 'T3', 'P_41', 'T4', 'P_42', 'T2'}'
1850	0.633	0.681	$ 16.67	'{'P_35', 'T5', 'P_37', 'T1', 'P_41', 'T4', 'P_42', 'T2'}'
1646	0.634	0.678	$ 16.39	'{'P_35', 'P_37', 'T1', 'P_41', 'T4', 'P_42', 'T2'}'
1219	0.635	0.675	$ 16.29	'{'P_35', 'P_37', 'P_41', 'T4', 'P_42', 'T2'}'
700	0.619	0.656	$ 16.20	'{'P_35', 'P_37', 'P_41', 'P_42', 'T2'}'
1994	0.605	0.656	$ 15.03	'{'P_35', 'T5', 'P_37', 'T1', 'T3', 'P_38', 'T4', 'P_42', 'T2'}'
1849	0.606	0.653	$ 14.65	'{'P_35', 'T5', 'P_37', 'T1', 'P_38', 'T4', 'P_42', 'T2'}'
1645	0.607	0.650	$ 14.37	'{'P_35', 'P_37', 'T1', 'P_38', 'T4', 'P_42', 'T2'}'
1218	0.608	0.647	$ 14.27	'{'P_35', 'P_37', 'P_38', 'T4', 'P_42', 'T2'}'
697	0.592	0.628	$ 14.18	'{'P_35', 'P_37', 'P_38', 'P_42', 'T2'}'
967	0.590	0.625	$ 14.14	'{'P_37', 'P_41', 'T4', 'P_42', 'T2'}'
490	0.575	0.606	$ 14.04	'{'P_37', 'P_42', 'T2', 'P_41'}'
1949	0.563	0.608	$ 12.88	'{'T5', 'P_37', 'T1', 'P_38', 'T3', 'T4', 'P_42', 'T2'}'
1729	0.563	0.604	$ 12.50	'{'T5', 'P_37', 'T1', 'P_38', 'T4', 'P_42', 'T2'}'
1435	0.564	0.601	$ 12.21	'{'P_37', 'T1', 'P_38', 'T4', 'P_42', 'T2'}'
966	0.564	0.598	$ 12.12	'{'P_37', 'P_38', 'T4', 'P_42', 'T2'}'
487	0.550	0.580	$ 12.02	'{'P_37', 'P_42', 'P_38', 'T2'}'
1254	0.531	0.566	$ 11.98	'{'P_35', 'T1', 'P_41', 'T4', 'P_42', 'T2'}'
771	0.531	0.563	$ 11.88	'{'P_35', 'P_41', 'T4', 'P_42', 'T2'}'
1835	0.519	0.560	$ 9.72	'{'P_35', 'T5', 'P_37', 'T1', 'T3', 'T4', 'P_42', 'T2'}'
1520	0.520	0.556	$ 9.34	'{'P_35', 'T5', 'P_37', 'T1', 'T4', 'P_42', 'T2'}'
1184	0.520	0.553	$ 9.05	'{'P_35', 'P_37', 'T1', 'T4', 'P_42', 'T2'}'
701	0.520	0.551	$ 8.96	'{'P_35', 'P_37', 'T4', 'P_42', 'T2'}'
295	0.507	0.534	$ 8.86	'{'P_37', 'P_35', 'P_42', 'T2'}'
1715	0.482	0.517	$ 7.56	'{'T5', 'P_37', 'T1', 'T3', 'T4', 'P_42', 'T2'}'
1310	0.482	0.514	$ 7.18	'{'T5', 'P_37', 'T1', 'T4', 'P_42', 'T2'}'

932	0.482	0.511	\$ 6.90	'{'P_37', 'T1', 'T4', 'P_42', 'T2'}'
491	0.482	0.509	\$ 6.80	'{'T4', 'P_37', 'P_42', 'T2'}'
175	0.470	0.493	\$ 6.71	'{'P_37', 'P_42', 'T2'}'
1575	0.433	0.466	\$ 5.31	'{'P_35', 'T5', 'T1', 'T3', 'T4', 'P_42', 'T2'}'
1114	0.434	0.463	\$ 4.93	'{'P_35', 'T5', 'T1', 'T4', 'P_42', 'T2'}'
736	0.434	0.460	\$ 4.64	'{'P_35', 'T1', 'T4', 'P_42', 'T2'}'
351	0.434	0.457	\$ 4.55	'{'T4', 'P_35', 'P_42', 'T2'}'
111	0.422	0.443	\$ 4.45	'{'P_35', 'P_42', 'T2'}'
1365	0.402	0.430	\$ 3.15	'{'T5', 'T1', 'T3', 'T4', 'P_42', 'T2'}'
862	0.402	0.427	\$ 2.77	'{'T5', 'T1', 'T4', 'P_42', 'T2'}'
526	0.402	0.424	\$ 2.49	'{'T4', 'P_42', 'T1', 'T2'}'
231	0.402	0.422	\$ 2.39	'{'T4', 'P_42', 'T2'}'
66	0.391	0.409	\$ 2.30	'{'P_42', 'T2'}'
841	0.355	0.379	\$ 1.14	'{'T5', 'T1', 'T3', 'T4', 'T2'}'
399	0.355	0.376	\$ 0.76	'{'T4', 'T1', 'T5', 'T2'}'
195	0.355	0.374	\$ 0.48	'{'T4', 'T1', 'T2'}'
65	0.355	0.372	\$ 0.38	'{'T4', 'T2'}'
11	0.346	0.360	\$ 0.29	'{'T2'}'
43	0.299	0.315	\$ 0.19	'{'T4', 'T1'}'
9	0.299	0.313	\$ 0.10	'{'T4'}'
0	0.290	0.303	\$ -	'set()'

Table S12. Pareto set for 25% storage tank capacity

N	Reliability Minimum	Reliability Maximum	Cost [10^6 USD/y]	Ext
2047	0.627	0.706	\$ 25.27	'{'T1', 'T3', 'P_37', 'T4', 'T5', 'P_41', 'P_38', 'P_36', 'P_42', 'P_35', 'T2'}'
2045	0.628	0.702	\$ 25.08	'{'T1', 'P_37', 'T4', 'T5', 'P_41', 'P_38', 'P_36', 'P_42', 'P_35', 'T2'}'
2023	0.630	0.699	\$ 24.98	'{'T1', 'P_37', 'T4', 'P_41', 'P_38', 'P_36', 'P_42', 'P_35', 'T2'}'
1915	0.630	0.693	\$ 24.89	'{'T1', 'P_37', 'T4', 'P_41', 'P_38', 'P_36', 'P_42', 'P_35'}'
1972	0.630	0.693	\$ 24.89	'{'P_37', 'T4', 'T5', 'P_41', 'P_38', 'P_36', 'P_42', 'P_35'}'
1978	0.630	0.693	\$ 24.89	'{'P_37', 'T4', 'P_41', 'P_38', 'P_36', 'P_42', 'P_35', 'T2'}'
2039	0.629	0.693	\$ 21.80	'{'T1', 'T3', 'P_37', 'T4', 'T5', 'P_41', 'P_38', 'P_42', 'P_35', 'T2'}'
2020	0.631	0.690	\$ 21.61	'{'T1', 'P_37', 'T4', 'T5', 'P_41', 'P_38', 'P_42', 'P_35', 'T2'}'
1918	0.632	0.686	\$ 21.51	'{'T1', 'P_37', 'T4', 'P_41', 'P_38', 'P_42', 'P_35', 'T2'}'
1635	0.624	0.674	\$ 21.42	'{'T1', 'P_37', 'T4', 'P_41', 'P_38', 'P_42', 'P_35'}'
1783	0.624	0.674	\$ 21.42	'{'P_37', 'T4', 'T5', 'P_41', 'P_38', 'P_42', 'P_35'}'
1798	0.624	0.674	\$ 21.42	'{'P_37', 'T4', 'P_41', 'P_38', 'P_42', 'P_35', 'T2'}'
1425	0.625	0.671	\$ 21.32	'{'P_37', 'T4', 'P_41', 'P_38', 'P_42', 'P_35'}'
991	0.609	0.651	\$ 21.23	'{'P_37', 'P_41', 'P_38', 'P_42', 'P_35'}'
1985	0.586	0.643	\$ 19.65	'{'T1', 'T3', 'P_37', 'T4', 'T5', 'P_41', 'P_38', 'P_42', 'T2'}'
1904	0.587	0.640	\$ 19.45	'{'T1', 'P_37', 'T4', 'T5', 'P_41', 'P_38', 'P_42', 'T2'}'
1636	0.588	0.636	\$ 19.36	'{'T1', 'P_37', 'T4', 'P_41', 'P_38', 'P_42', 'T2'}'
1166	0.580	0.625	\$ 19.26	'{'T1', 'P_37', 'T4', 'P_41', 'P_38', 'P_42'}'
1403	0.580	0.625	\$ 19.26	'{'P_37', 'T4', 'T5', 'P_41', 'P_38', 'P_42'}'
1426	0.580	0.625	\$ 19.26	'{'P_37', 'T4', 'P_41', 'P_38', 'P_42', 'T2'}'
914	0.581	0.622	\$ 19.17	'{'P_37', 'T4', 'P_41', 'P_38', 'P_42'}'
508	0.565	0.602	\$ 19.07	'{'P_41', 'P_38', 'P_42', 'P_37'}'
1990	0.541	0.593	\$ 16.48	'{'T1', 'T3', 'P_37', 'T4', 'T5', 'P_41', 'P_42', 'P_35', 'T2'}'
1909	0.542	0.590	\$ 16.29	'{'T1', 'P_37', 'T4', 'T5', 'P_41', 'P_42', 'P_35', 'T2'}'
1641	0.543	0.586	\$ 16.20	'{'T1', 'P_37', 'T4', 'P_41', 'P_42', 'P_35', 'T2'}'
1172	0.535	0.575	\$ 16.10	'{'T1', 'P_37', 'T4', 'P_41', 'P_42', 'P_35'}'
1409	0.535	0.575	\$ 16.10	'{'P_37', 'T4', 'T5', 'P_41', 'P_42', 'P_35'}'
1431	0.535	0.575	\$ 16.10	'{'P_37', 'T4', 'P_41', 'P_42', 'P_35', 'T2'}'
920	0.536	0.572	\$ 16.01	'{'P_37', 'T4', 'P_41', 'P_42', 'P_35'}'

1994	0.518	0.568	$ 14.46	'{'T1', 'T3', 'P_37', 'T4', 'T5', 'P_38', 'P_42', 'P_35', 'T2'}'
1913	0.519	0.565	$ 14.27	'{'T1', 'P_37', 'T4', 'T5', 'P_38', 'P_42', 'P_35', 'T2'}'
1645	0.519	0.562	$ 14.18	'{'T1', 'P_37', 'T4', 'P_38', 'P_42', 'P_35', 'T2'}'
1178	0.512	0.551	$ 14.08	'{'T1', 'P_37', 'T4', 'P_38', 'P_42', 'P_35'}'
1415	0.512	0.551	$ 14.08	'{'P_37', 'T4', 'T5', 'P_38', 'P_42', 'P_35'}'
1435	0.512	0.551	$ 14.08	'{'P_37', 'T4', 'P_38', 'P_42', 'P_35', 'T2'}'
926	0.513	0.548	$ 13.99	'{'P_37', 'T4', 'P_38', 'P_42', 'P_35'}'
654	0.497	0.532	$ 13.95	'{'T1', 'P_37', 'T4', 'P_41', 'P_42'}'
900	0.497	0.532	$ 13.95	'{'P_37', 'T4', 'T5', 'P_41', 'P_42'}'
921	0.497	0.532	$ 13.95	'{'P_37', 'T4', 'P_41', 'P_42', 'T2'}'
520	0.498	0.530	$ 13.89	'{'P_38', 'P_42', 'P_37', 'P_35'}'
444	0.497	0.529	$ 13.85	'{'P_41', 'P_37', 'P_42', 'T4'}'
1830	0.481	0.526	$ 12.31	'{'T1', 'T3', 'P_37', 'T4', 'T5', 'P_38', 'P_42', 'T2'}'
1626	0.481	0.523	$ 12.12	'{'T1', 'P_37', 'T4', 'T5', 'P_38', 'P_42', 'T2'}'
1179	0.482	0.519	$ 12.02	'{'T1', 'P_37', 'T4', 'P_38', 'P_42', 'T2'}'
658	0.475	0.509	$ 11.93	'{'T1', 'P_37', 'T4', 'P_38', 'P_42'}'
904	0.475	0.509	$ 11.93	'{'P_37', 'T4', 'T5', 'P_38', 'P_42'}'
927	0.475	0.509	$ 11.93	'{'P_37', 'T4', 'P_38', 'P_42', 'T2'}'
448	0.475	0.506	$ 11.83	'{'P_42', 'P_37', 'P_38', 'T4'}'
188	0.462	0.490	$ 11.74	'{'P_38', 'P_42', 'P_37'}'
1835	0.444	0.484	$ 9.15	'{'T1', 'T3', 'P_37', 'T4', 'T5', 'P_42', 'P_35', 'T2'}'
1631	0.444	0.481	$ 8.96	'{'T1', 'P_37', 'T4', 'T5', 'P_42', 'P_35', 'T2'}'
1184	0.444	0.478	$ 8.86	'{'T1', 'P_37', 'T4', 'P_42', 'P_35', 'T2'}'
664	0.438	0.468	$ 8.76	'{'T1', 'P_37', 'T4', 'P_42', 'P_35'}'
910	0.438	0.468	$ 8.76	'{'P_37', 'T4', 'T5', 'P_42', 'P_35'}'
932	0.438	0.468	$ 8.76	'{'P_37', 'T4', 'P_42', 'P_35', 'T2'}'
454	0.438	0.465	$ 8.67	'{'P_37', 'P_42', 'T4', 'P_35'}'
194	0.426	0.450	$ 8.57	'{'P_42', 'P_37', 'P_35'}'
1499	0.411	0.447	$ 6.99	'{'T1', 'T3', 'P_37', 'T4', 'T5', 'P_42', 'T2'}'
1163	0.412	0.444	$ 6.80	'{'T1', 'P_37', 'T4', 'T5', 'P_42', 'T2'}'
665	0.412	0.441	$ 6.71	'{'T1', 'P_37', 'T4', 'P_42', 'T2'}'
272	0.406	0.432	$ 6.61	'{'T1', 'P_37', 'P_42', 'T4'}'
439	0.406	0.432	$ 6.61	'{'P_37', 'P_42', 'T4', 'T5'}'
455	0.406	0.432	$ 6.61	'{'P_37', 'P_42', 'T4', 'T2'}'
152	0.406	0.429	$ 6.52	'{'P_37', 'P_42', 'T4'}'
43	0.394	0.415	$ 6.42	'{'P_42', 'P_37'}'
1540	0.370	0.402	$ 4.74	'{'T1', 'T3', 'T4', 'T5', 'P_42', 'P_35', 'T2'}'
1204	0.370	0.399	$ 4.55	'{'T1', 'T4', 'T5', 'P_42', 'P_35', 'T2'}'
701	0.370	0.396	$ 4.45	'{'T1', 'T4', 'P_42', 'P_35', 'T2'}'
293	0.365	0.388	$ 4.35	'{'T1', 'P_42', 'T4', 'P_35'}'
469	0.365	0.388	$ 4.35	'{'P_42', 'T4', 'P_35', 'T5'}'
491	0.365	0.388	$ 4.35	'{'P_42', 'T4', 'P_35', 'T2'}'
173	0.365	0.386	$ 4.26	'{'P_42', 'T4', 'P_35'}'
64	0.355	0.373	$ 4.16	'{'P_42', 'P_35'}'
1058	0.343	0.371	$ 2.58	'{'T1', 'T3', 'T4', 'T5', 'P_42', 'T2'}'
680	0.343	0.368	$ 2.39	'{'T1', 'T4', 'T5', 'P_42', 'T2'}'
294	0.343	0.366	$ 2.30	'{'T1', 'P_42', 'T4', 'T2'}'
81	0.338	0.358	$ 2.20	'{'T1', 'P_42', 'T4'}'
158	0.338	0.358	$ 2.20	'{'P_42', 'T4', 'T5'}'
174	0.338	0.358	$ 2.20	'{'P_42', 'T4', 'T2'}'
36	0.338	0.356	$ 2.10	'{'P_42', 'T4'}'
9	0.328	0.344	$ 2.01	'{'P_42'}'
574	0.303	0.327	$ 0.57	'{'T1', 'T3', 'T4', 'T5', 'T2'}'
280	0.303	0.324	$ 0.38	'{'T1', 'T2', 'T4', 'T5'}'
83	0.303	0.322	$ 0.29	'{'T1', 'T4', 'T2'}'
13	0.299	0.315	$ 0.19	'{'T1', 'T4'}'

32	0.299	0.315	$ 0.19	'{'T4', 'T5'}'
38	0.299	0.315	$ 0.19	'{'T4', 'T2'}'
3	0.299	0.313	$ 0.10	'{'T4'}'
0	0.290	0.303	$ -	'set()'

References

[1] S. Jenkins, "The Chemical Engineering Plant Cost Index," Access Intelligence, 2025. [Online]. Available: https://www.chemengonline.com/pci-home

[2] AmeriTex Pipe & Products LLC, "How Much Does Concrete Pipe Cost?" AmeriTex Pipe & Products LLC, Dallas, TX, May 11, 2022. [Online]. Available: https://www.ameritexpipe.com/how-much-does-concrete-pipe-cost/

[3] CST Industries, Inc, "Wastewater Covers & Storage Tanks," USA, 2025. [Online]. Available: https://www.cstindustries.com/waste-water-storage-tanks-manufacturer/

[4] Matches, *Matches' Process Equipment Cost Estimates*. (2014). [Online]. Available: https://www.matche.com/equipcost/Default.html