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Probabilistic Corrosion-Driven LCC Comparison for Steel Truss Bridges: Risk-Return Analysis of Weathering Steel, Stainless Steel, and Painted Carbon Steel

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Abstract. The selection of materials and corresponding protection decisions for Truss steel bridges are often not dominated by the initial steel cost, but mainly depend on the maintenance demand driven by corrosion, the impact on users and the potential risk consequences. This article innovatively proposes an analytical framework that is publicly available and reproducible. The framework cleverly combines probabilistic corrosion models related to the environment with simplified but truss focused system reliability proxy methods, specifically covering key member multi state capacity loss and weighted k taking n/minimum cut set dilation. This framework is embedded in the Life Cycle Cost (LCC) model, which comprehensively includes daily costs, user interruption costs caused by recoating, and probability weighted consequence costs. Through Monte Carlo simulation, LCC distributions and return probability curves were generated for three different corrosion levels and three alternative materials (painted carbon steel, weathering steel, and stainless steel), highlighting the LCC inversion conditions and quantifying the sensitivity of investment returns and expected savings to discount rates, coating life uncertainties, and system dependencies.

Keywords: Steel truss bridge, atmospheric corrosion, system reliability, life-cycle cost, payback probability

1. Introduction

For steel truss bridges exposed to atmospheric corrosion, the economic ranking of material/protection choices is frequently determined by whole-life maintenance, traffic/user disruption, and risk consequences rather than the unit price of steel. Recent LCC studies of steel bridge alternatives show that higher-CAPEX corrosion-resistant options can become economically favorable when recoating cycles and user costs are significant [1]. Reliability-aware LCC optimization further indicates that system failure probability and consequence cost can amplify the value of corrosion-resistant materials under harsh environments [2].

However, much of the existing literature and decision templates focus on girder bridges or simplified series systems. Direct transfer to truss bridges requires an explicit representation of system effects: multiple load paths, critical member identification, and the impact of correlation

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(common micro-environments, drainage details) on system failure. Recent work has advanced probabilistic corrosion and time-variant behavior for steel truss bridges [3-5], while spatial variability/correlation modeling using Bayesian networks has improved the tractability of network-level dependence in aging steel bridges [6-8]. Dynamic Bayesian network and Markov decision process methods have been used for inspection and maintenance planning under uncertainty [9]. Tractable system-reliability approximations based on cut-set reasoning and sequence reduction have also emerged [10,11]. Nevertheless, a reproducible, engineering-implementable Pf_sys(t) module that can be coupled to LCC and run in Excel/Python remains limited.

This paper addresses this gap by proposing a practical framework for corrosion-driven LCC comparison of truss bridges, using a key-member multi-state capacity loss model and a weighted k-out-of-n / inflation proxy for system failure. The approach retains implementability while allowing sensitivity and risk–return interpretation valued by Scopus-indexed journals. The contributions are: (i) a unified Monte Carlo workflow producing LCC distributions and payback probability curves; (ii) a system-reliability proxy suitable for trusses and compatible with minimal cut-set ideas; and (iii) a sensitivity analysis reporting elasticity and payback-year shifts under key uncertainties.

2. Methodology

Atmospheric corrosion depth is modelled as D(t) = k_corr * t, where k_corr follows a lognormal distribution conditioned on corrosivity class. For the painted baseline, coating life T_c is modelled as Weibull(eta, beta), producing stochastic recoating times. This structure aligns with recent probabilistic corrosion modelling for bridge steels and weathering steel applications [7].

A critical member i is represented by an initial resistance R0,i reduced by corrosion-induced section loss: R_i(t) = R0,i * g_i(D(t)), where g_i(D) = max(alpha_min, 1 - a_i*D)^(p_i). Resistance and demand are treated as lognormal random variables, yielding a closed-form member failure probability Pf_i(t).

To avoid prohibitive enumeration of truss failure sequences, system survival is approximated by a weighted geometric aggregation of member survivals with an inflation factor lambda_sys to represent correlation and neglected cut-set interactions: Pf_sys(t) = 1 - (∏_i (1 - Pf_i(t))^(w_i))^(lambda_sys). This proxy is compatible with minimal cut-set reasoning and can be calibrated to more detailed models; efficient cut-set search and sequence-reduction methods support this engineering approximation for decision studies [10,11].

The present-value life-cycle cost over horizon T is LCC(T) = C0 + PV(Ca) + PV(Cr) + PV(Crisk). Here, Ca is an annual routine cost; Cr is the per-event recoating/user cost triggered by coating failures; and Crisk is computed by discounting the incremental system failure probability multiplied by a consequence cost C_cons.

Uncertainty in k_corr and coating life is propagated via Monte Carlo simulation. In addition to horizon LCC distributions, the payback probability curve is reported for each alternative A relative to the painted baseline B: P_PB(t) = P{LCC_A(t) < LCC_B(t)}. The median payback year is the first t for which P_PB(t) >= 0.5.

3. Input parameters and case study

The case study considers three corrosivity classes and three alternatives: painted carbon steel (baseline), weathering steel, and stainless steel. The analysis horizon is T=75 years. Input parameters follow the provided Excel template; Table 1, Table 2, Table 3 summarize the environment, member, and cost assumptions used in the reproducible example.

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Table 1. Environment-dependent corrosion rate and coating life parameters used in the case study

Env_ID	Environment	E[k_corr] (mm/yr)	COV(k_corr)	Weibull η of T_c (yr)	Weibull β of T_c (-)
1	Inland / mild (example)	0.030	0.30	15.0	2.50
2	Industrial (example)	0.050	0.35	12.0	2.20
3	Coastal / marine (example)	0.080	0.40	10.0	2.00

Note: k_corr is lognormal with listed mean and COV. Coating life T_c follows Weibull(η,β).

Table 2. Critical member parameters for the simplified truss reliability model

Member	Name	R0 mean (kN)	COV_R	S mean (kN)	COV_S	a (1/mm)	p (-)	weight w_i
1	Top chord (comp)	13,750	0.12	4,200	0.15	0.1200	2.00	1.00
2	Bottom chord (tens)	13,000	0.10	3,900	0.15	0.1000	1.00	1.00
3	Diagonal (comp)	6,500	0.15	1,900	0.20	0.1400	2.00	0.80
4	Diagonal (tens)	6,000	0.12	1,700	0.20	0.1200	1.00	0.80
5	Vertical (comp)	4,500	0.18	1,200	0.25	0.1600	2.00	0.60
6	Vertical (tens)	4,000	0.15	1,050	0.25	0.1400	1.00	0.60
7	Gusset/connection group	2,250	0.20	650	0.25	0.2000	1.50	0.70
8	Redundancy-critical member	5,500	0.15	1,600	0.20	0.1500	1.50	0.90

Note: Member failure probabilities are aggregated using the weighted system proxy.

Table 3. Cost and material/protection parameters for the evaluated alternatives

Alt_ID	Alternative	CAPEX C0 ($M)	k_corr factor	Annual cost C_a ($M/yr)	Recoating+user cost C_r/event ($M)	Consequence cost C_cons ($M)
1	Painted Carbon Steel (coated)	1.000	1.00	0.010	0.120	5.000
2	Weathering Steel (uncoated)	1.150	0.60	0.012	0.000	5.000
3	Stainless Steel (low-maintenance)	1.400	0.20	0.012	0.000	5.000

Note: Recoating cost per event may include both direct and user costs in this example template.

4. Results

Table 4. Summary of simulated LCC and system failure probability at T=75 years, and median payback year relative to painted carbon steel

Environment	Alternative	LCC mean ($M)	LCC std ($M)	LCC p05 ($M)	LCC p95 ($M)	Mean Pf_sys(T)	Payback year (P=0.5)
Inland / mild (example)	Painted Carbon Steel (coated)	2.013	0.609	1.466	3.406	0.311	
Inland / mild (example)	Weathering Steel (uncoated)	1.536	0.070	1.508	1.634	0.027	31

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Table 4. (continued)

Inland / mild (example)	Stainless Steel (low-maintenance)	1.757	0.000	1.757	1.757	0.000	71
Industrial (example)	Painted Carbon Steel (coated)	3.122	0.871	1.756	4.306	0.787	
Industrial (example)	Weathering Steel (uncoated)	1.848	0.520	1.513	2.940	0.252	13
Industrial (example)	Stainless Steel (low-maintenance)	1.758	0.002	1.757	1.759	0.001	20
Coastal / marine (example)	Painted Carbon Steel (coated)	3.910	0.633	3.046	4.962	0.966	
Coastal / marine (example)	Weathering Steel (uncoated)	2.785	0.876	1.541	3.763	0.695	12
Coastal / marine (example)	Stainless Steel (low-maintenance)	1.772	0.040	1.757	1.839	0.015	15

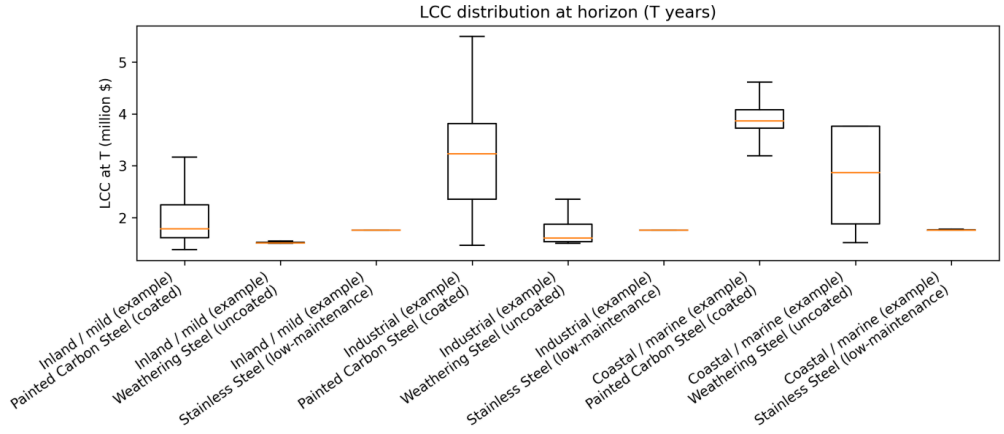


Figure 1. Distribution of present-value Life-Cycle Cost (LCC) across environments and alternatives (T=75 years). (picture credit : original)

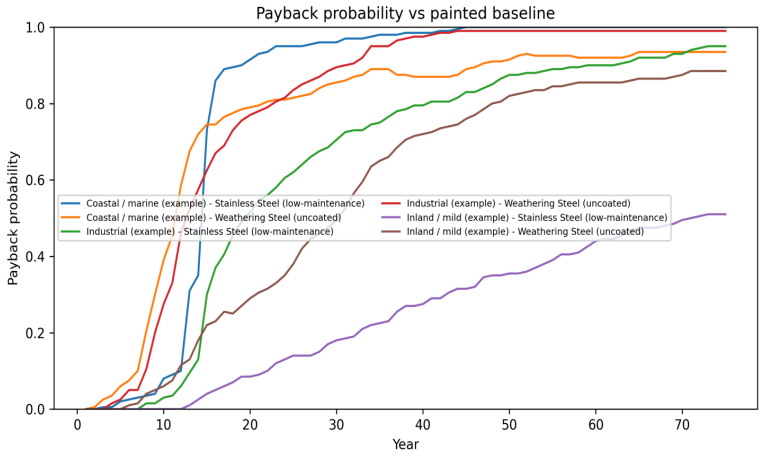


Figure 2. Payback probability P{LCC_alt(t) < LCC_painted(t)} over time for weathering steel and stainless steel under three environments. (picture credit : original)

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Across environments, LCC variation is driven primarily by recoating/user costs and the probability-weighted consequence term. In the coastal scenario, the painted baseline exhibits high maintenance frequency and wide variability due to the Weibull tail of coating life, whereas weathering and stainless options trade higher CAPEX for reduced maintenance. The magnitude of risk cost depends on the chosen system proxy and the dependency inflation factor \lambda_sys, which also influences payback probability, as shown in Table 4, Figure 1, Figure 2 and Figure 3.

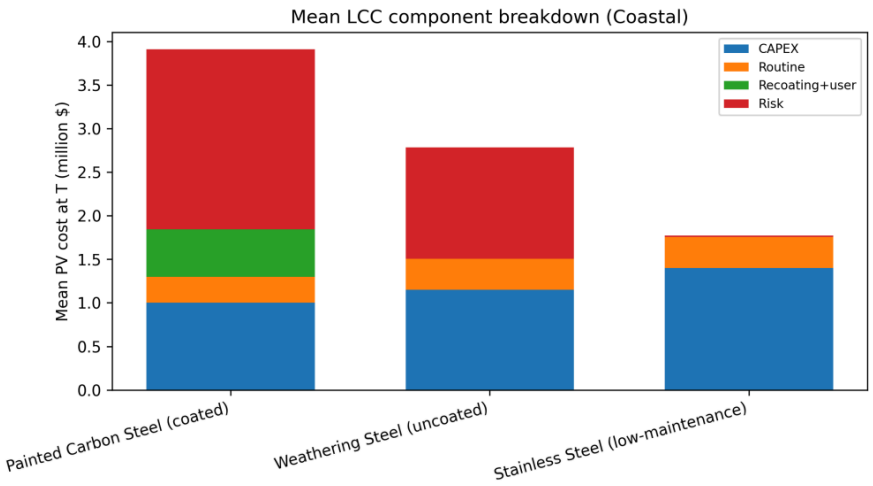


Figure 3. Mean LCC component breakdown for the coastal environment (CAPEX, routine, recoating+user, and risk consequence cost). (picture credit : original)

5. Sensitivity analysis and discussion

Table 5. One-at-a-time sensitivity summary for the coastal scenario (stainless vs painted baseline)

Parameter	Savings base ($M)	Savings low ($M)	Savings high ($M)	ΔSavings low ($M)	ΔSavings high ($M)	Elasticity	PB50 base (yr)	PB50 low (yr)	PB50 high (yr)	ΔPB50 low (yr)	ΔPB50 high (yr)
Discount rate r	2.441	4.245	1.175	1.804	-1.266	-0.94	15	14	17	-1	2
Coating life scale η	2.441	2.609	2.006	0.168	-0.435	-0.41	15	14	15	-1	0
System inflation λ_sys	2.441	2.293	2.163	-0.148	-0.278	-0.11	15	15	15	0	0
Corrosion rate mean k_corr	2.441	2.122	2.192	-0.319	-0.249	0.07	15	15	15	0	0
Consequence cost C_cons	2.441	1.253	4.205	-1.188	1.763	0.81	15	19	11	4	-4

Note: All savings are in $M (painted minus stainless at T=75). PB50 is the first year with payback probability ≥0.5.

Interpretability is critical for journal publishability. This paper quantifies how key assumptions drive expected savings and payback (coastal scenario; stainless vs painted baseline), as shown in Table 5. Reported metrics include elasticity of expected savings and shifts in median payback year (PB50) under one-at-a-time parameter perturbations, as shown in Figure 4. The sensitivity results also motivate using more rigorous DBN+MDP/POMDP methods as theoretical upper bounds, while retaining a practical threshold-trigger policy for engineering implementation [9,12].

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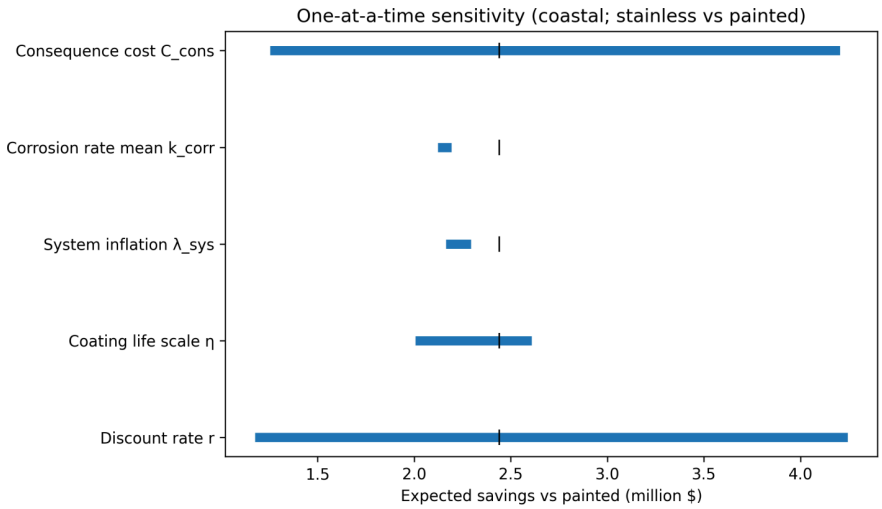


Figure 4. Tornado plot of sensitivity: range of expected savings under one-at-a-time parameter changes (coastal; stainless vs painted). (picture credit : original)

6. Conclusion

Economic assessment of material/protection for steel truss bridges should rely on full LCC, including maintenance, user disruption, and risk consequence costs, rather than CAPEX alone; LCC inversion can occur when recoating/user costs dominate. For trusses, a key-member multi-state model combined with a minimal cut-set-inspired weighted system proxy provides a more credible yet implementable Pf,sys(t), materially affecting payback probability and payback year. Threshold-trigger maintenance strategies provide a reproducible engineering baseline; sensitivity analysis can identify robust threshold ranges, while DBN+MDP/POMDP formulations can serve as theoretical upper bounds for future research. Future work should parameterize local corrosion at joints and drainage details and apply Bayesian updating using inspection/monitoring data; system approximation can be enhanced by adaptive cut-set selection driven by evolving failure scenarios.

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