Maintenance-Aware Digital Twin for Low-Carbon Production: A Resilient Stochastic Optimization Framework for Industry 5.0

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This document provides the statistical validation for the MADO (Maintenance-Aware Design and Operations) framework. It supports research into using sustainability-weighted objective functions to identify resilient production policies in stochastic Industry 5.0 environments. The raw simulation data used for these tests can be found in the /Digital-Twin-Project folder of this repository.

S1. Detailed Statistical Validation

The study identifies Scenario S5 as the optimal policy based on robust means. To validate this ranking statistically, this section provides the granular hypothesis testing results.

Global Significance Tests We performed omnibus tests to determine if the differences between scenarios (S1–S6) were statistically significant across the key performance indicators. As shown in Table S1, the p-value for Profit is well below the $\alpha = 0.05$ threshold, rejecting the null hypothesis that all strategies perform equally. The hypothesis tests shown in Table S1 were performed on the raw Monte Carlo results (N=30) provided in this repository as Baseline_Profit_Only_Results.csv through Optimized_Sustainability_Results.csv.

Table S1. Global significance tests across scenarios (ANOVA/Kruskal-Wallis).

KPI	ANOVA p	Kruskal–Wallis p
profit	0.0003184	0.001877
avgLead	0.1523	0.1456
avgTard	0.1401	0.02792
energyPerPart_kWh	0.07473	0.06677

Post-Hoc Pairwise Comparisons Following the omnibus test, Table S2 details the Holm-corrected p-values using Welch's t-test and the Mann-Whitney (MW) test for the profit metric. This confirms that the performance gap between the "Profit-Only" strategy (S1) and the "Weighted Sustainability" strategy (S5) is statistically significant (p < 0.05).

Table S2. Significant post-hoc differences for profit (Holm-corrected p-values).

Scenario A	Scenario B	Welch t Holm p	MW Holm p
S1	S4	0.0005674	0.0013
S1	S6	0.02845	0.1179
S1	S5	0.04222	0.04902

The optimization of S5 is statistically superior to S1 ($p < 0.05$), confirming that the "Profit-Only" trap is a statistically significant phenomenon, not random noise.

S2. Distributional Evidence of Resilience

To validate the "Deterministic Substitution" mechanism described in the manuscript, we analyzed the empirical distributions of Lead Time and Tardiness. These plots demonstrate how the optimal policy mitigates "tail risk."

Lead Time Distributions

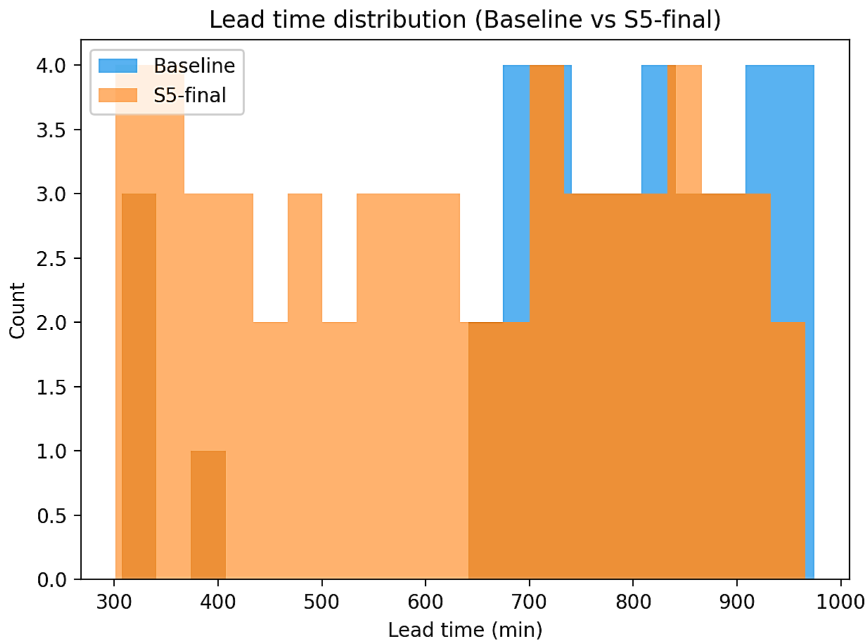

Figure S1. Lead-time histogram comparison (Baseline vs S5-final).

Note how the S5 configuration (orange) shifts the distribution mass to the left and reduces the frequency of extreme outliers observed in the Baseline (blue).

Empirical Cumulative Distribution Function (ECDF)

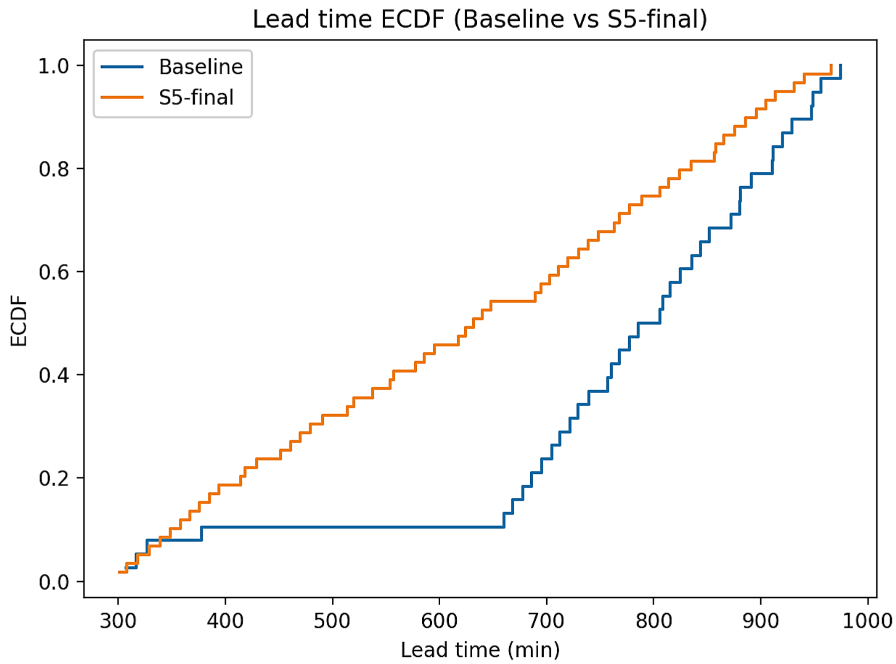

Figure S2. Lead-time Empirical Cumulative Distribution Function (ECDF).

The S5 curve (orange) demonstrates stochastic dominance over the Baseline (blue), indicating a systemic reduction in the probability of long flow times across all percentiles.

S3. Optimization Convergence Traces

To ensure the reported optimization results represent stable global optima rather than premature convergence, Figure S3 provides the full search history.

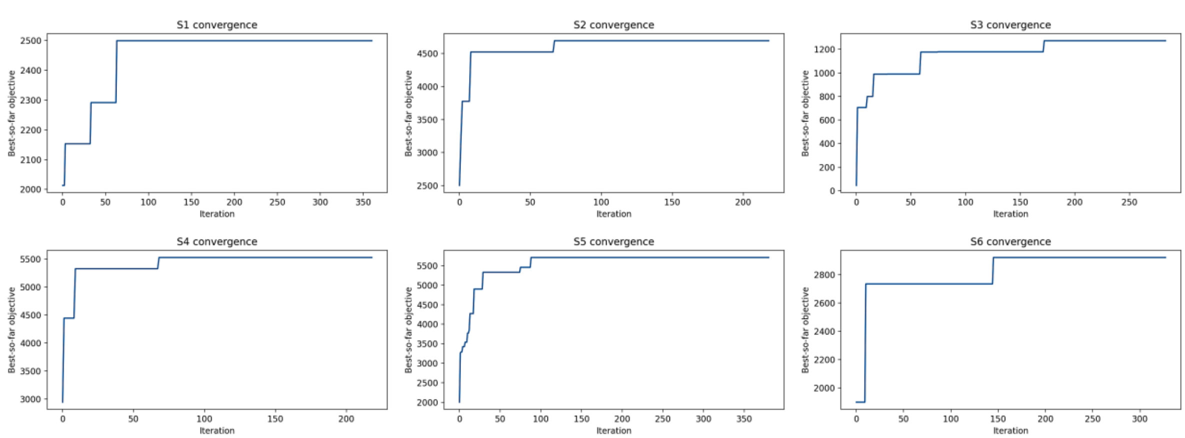

Figure S3. Full optimization convergence traces (Best-so-far Objective vs. Iteration).

All scenarios achieved trajectory stability prior to the 400th iteration, confirming that the 500-iteration computational budget was sufficient for this solution space.

Note: The objective value J corresponds to the variable Z defined in Equation 4 of the manuscript.

S4. Model Implementation & Traceability

The following screenshots document the specific AnyLogic experimental configuration used to generate the dataset, ensuring reproducibility.

Optimization Engine Configuration

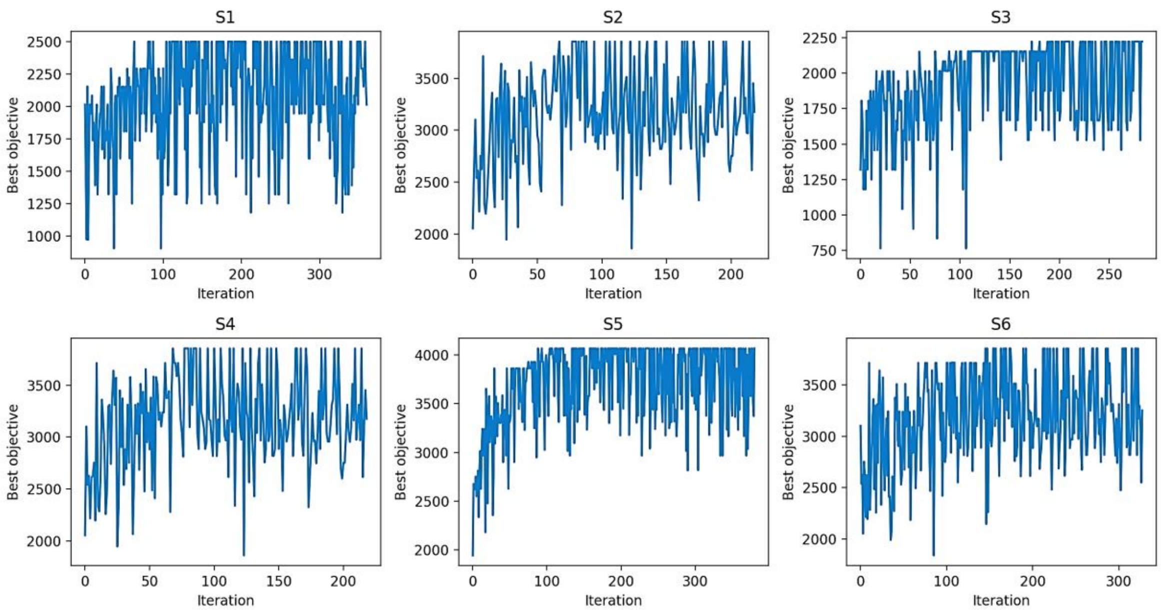

Figure S4. AnyLogic Optimization Experiment Interface, displaying the decision variable ranges and constraint configuration.

Monte Carlo Verification Interface

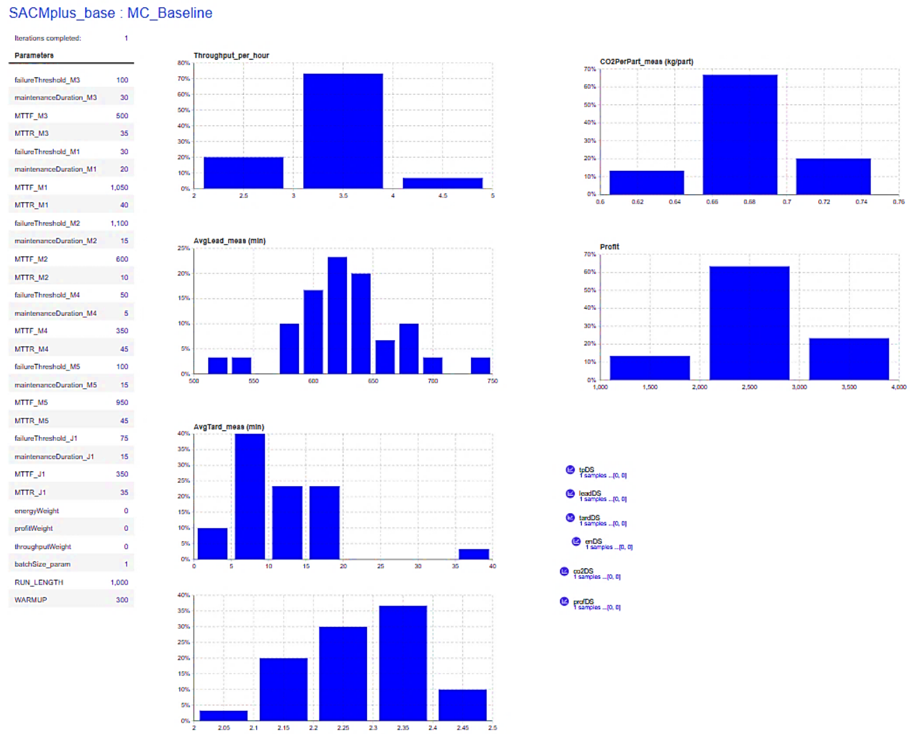

Figure S5. Monte Carlo Experiment Dashboard (Verification Phase).

This interface was used to run the N=30 replications for the "Dual-Phase" verification protocol described in Section 3.5 of the manuscript.