

Supplementary Information

Bottleneck-aware explainable learning-to-dispatch improves simulated throughput in dynamic flexible manufacturing systems

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Evidence boundary

All numerical findings in the manuscript are generated by the supplied benchmark-derived discrete-event simulation. The study uses the public Brandimarte MK01-MK05 static job-operation templates and nominal machine processing times. The raw third-party benchmark files are not included in this supplementary package; exact public retrieval sources and SHA-256 checksums are provided in Supplementary Data S1. Arrivals, due dates, product families, processing variability, setups, failures, repairs, and every reported performance metric are synthetic simulation outputs. The environment is not a synchronized or plant-calibrated operational digital twin. No employer, customer, or other proprietary production data are included or implied.

Reproduction files

The separately uploaded Supplementary Data S1 reproducibility archive contains the simulator, coefficient-search and evaluation scripts, selected models, complete replication-level results, random seeds, statistical outputs, decision explanations, figure-generation files, and a benchmark retrieval utility. It intentionally does not redistribute the Brandimarte instance files. Running `prepare_brandimarte_inputs.py` obtains MK01-MK05 from the public SchedulingLab repository and verifies the downloaded files against the included SHA-256 manifest before the simulations are rerun.

Supplementary Table S1. Benchmark characteristics and experimental partition.

Instance	Jobs	Machines	Operations	Mean eligibility	Mean minimum workload	Use
MK01	10	6	55	2.091	15.300	Coefficient search
MK02	10	6	58	4.103	14.000	Coefficient search
MK03	15	8	150	3.007	54.133	Validation/model selection
MK04	15	8	90	1.911	21.600	Held-out test
MK05	15	4	106	1.708	44.800	Held-out test

Supplementary Table S2. Dynamic disturbance-scenario parameters.

Scenario	Target util.	Processing CV	Failure prob.	Mean repair	Setup ratio	Rush prob.
Nominal	0.88	0.05	0.01	3.0	0.08	0.04
Variability	0.91	0.20	0.01	3.0	0.12	0.08
Breakdowns	0.91	0.08	0.08	9.0	0.12	0.08
Combined	0.94	0.22	0.08	10.0	0.18	0.12

Supplementary Table S3. Selected BA-XLD coefficients at full stored precision.

Feature	Coefficient
processing	1.873406223
setup_change	1.078895072
slack	-0.149769583
remaining_work	1.087012645
next_flexibility	0.825148457
age	-0.686868142
bottleneck_feed	0.016297030
completion_bias	-0.568782720

Training utility: 0.089245; validation utility: 0.199968; combined selection score: 0.150143.

Supplementary Table S4. Full policy-by-scenario performance summary.

Scenario	Policy	Throughput	SD	Tardiness	WIP	Util.	Setup	Flow time
Nominal	BA-XLD	14.690	9.116	24.792	21.629	0.776	98.714	81.019
Nominal	SPT	14.012	8.569	38.399	22.735	0.781	125.574	97.520
Nominal	MINSLACK	12.774	7.375	48.912	25.154	0.787	108.436	111.093
Nominal	EDD	12.750	7.317	48.186	25.267	0.772	96.970	108.870
Nominal	COMPOSITE	12.833	7.516	44.503	25.067	0.793	90.894	104.844
Nominal	SETUP	12.619	7.979	41.316	25.899	0.791	52.118	99.550
Nominal	Standard-Q	11.988	6.553	39.314	25.113	0.782	112.956	101.578
Variability	BA-XLD	14.500	8.919	30.862	22.980	0.772	148.815	87.644
Variability	SPT	13.357	7.976	43.486	24.631	0.771	185.430	103.723
Variability	MINSLACK	12.500	6.952	52.082	26.569	0.777	159.348	114.831
Variability	EDD	12.357	6.960	49.289	26.478	0.765	144.783	109.939
Variability	COMPOSITE	12.452	7.288	47.803	26.855	0.789	136.524	108.763
Variability	SETUP	12.381	7.480	43.441	27.459	0.796	76.356	102.486
Variability	Standard-Q	11.381	5.928	42.688	26.849	0.773	164.529	104.824
Breakdowns	BA-XLD	12.762	8.002	41.219	30.137	0.689	128.379	97.957
Breakdowns	SPT	11.810	7.324	58.087	31.877	0.693	169.392	117.974
Breakdowns	MINSLACK	10.940	6.276	71.492	33.535	0.707	143.229	135.351
Breakdowns	EDD	10.750	5.930	67.791	33.392	0.700	130.377	130.054
Breakdowns	COMPOSITE	10.488	6.125	63.897	34.861	0.711	113.001	123.897
Breakdowns	SETUP	10.214	6.235	57.952	35.119	0.729	55.500	118.473
Breakdowns	Standard-Q	10.821	5.884	64.809	33.165	0.703	137.004	128.166
Combined	BA-XLD	11.750	7.213	47.316	31.238	0.657	177.746	103.342
Combined	SPT	10.881	6.423	67.736	33.140	0.653	235.922	125.831
Combined	MINSLACK	10.298	5.653	77.501	33.986	0.674	200.012	139.831
Combined	EDD	10.012	5.392	72.081	34.057	0.668	179.424	133.030
Combined	COMPOSITE	9.571	5.156	71.412	35.752	0.680	158.990	129.783
Combined	SETUP	9.274	5.361	64.696	36.146	0.704	77.540	123.274
Combined	Standard-Q	10.190	5.337	69.833	33.573	0.672	183.483	131.834

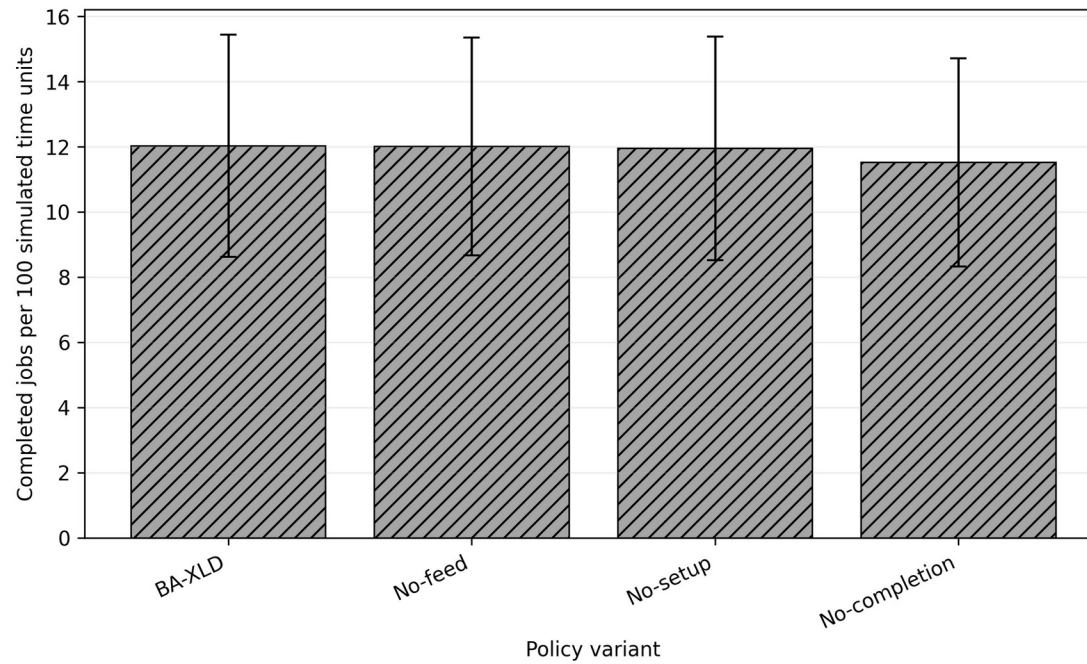
Throughput is completed jobs per 100 simulated time units. Tardiness, setup, and flow time are in simulated time units; WIP is time-average jobs; Util. is productive utilization.

Supplementary Table S5. All 16 prespecified paired superiority tests.

Scenario	Baseline	n	Gain	W	Raw P	BH P	r_rb	Mean-diff 95% CI
Nominal	Standard-Q	20	22.54%	175.5	0.000594	0.000893	0.847	[1.560, 3.940]
Nominal	COMPOSITE	20	14.47%	151.0	0.000208	0.000417	0.974	[1.060, 2.690]
Nominal	SPT	20	4.84%	114.0	0.001079	0.001328	0.900	[0.357, 1.000]
Nominal	SETUP	20	16.42%	188.0	9.08e-05	0.000398	0.979	[1.369, 2.810]
Variability	Standard-Q	20	27.41%	130.5	0.000614	0.000893	0.919	[1.762, 4.476]
Variability	COMPOSITE	20	16.44%	168.5	0.000149	0.000398	0.971	[1.119, 3.167]
Variability	SPT	20	8.56%	163.0	0.000366	0.000651	0.906	[0.667, 1.690]
Variability	SETUP	20	17.12%	170.0	0.000116	0.000398	0.988	[1.036, 3.429]
Breakdowns	Standard-Q	20	17.93%	122.0	0.002579	0.002948	0.794	[0.964, 3.000]
Breakdowns	COMPOSITE	20	21.68%	190.0	6.45e-05	0.000398	1.000	[1.417, 3.179]
Breakdowns	SPT	20	8.06%	153.0	0.000145	0.000398	1.000	[0.583, 1.357]
Breakdowns	SETUP	20	24.94%	189.0	7.71e-05	0.000398	0.989	[1.500, 3.690]
Combined	Standard-Q	20	15.30%	125.0	0.010795	0.010795	0.634	[0.655, 2.512]
Combined	COMPOSITE	20	22.76%	174.0	0.000730	0.000973	0.832	[1.214, 3.155]
Combined	SPT	20	7.99%	104.0	0.006156	0.006566	0.733	[0.333, 1.452]
Combined	SETUP	20	26.70%	167.5	0.000177	0.000405	0.959	[1.369, 3.750]

Supplementary Table S6. Combined-scenario ablation summary.

Variant	Mean throughput	SD	95% CI
BA-XLD	12.0357	7.2902	[8.6238, 15.4477]
No-feed	12.0119	7.1481	[8.6665, 15.3573]
No-setup	11.9524	7.3401	[8.5171, 15.3876]
No-completion	11.5238	6.8330	[8.3258, 14.7218]



Supplementary Figure S1. Combined-scenario ablation sensitivity. Points show mean throughput for BA-XLD and the three one-feature ablations; error bars are 95% confidence intervals for the displayed ablation experiment. The separate seed family used for this analysis is distinct from the main held-out comparison.

Supplementary Table S7. Global additive-explanation summary for the representative MK05 combined-disturbance run.

Feature	Mean absolute contribution	Mean signed contribution
processing	2.761565	-2.742312
remaining_work	1.014050	-0.784560
setup_change	0.706439	0.706439
age	0.502750	-0.045720
next_flexibility	0.485162	-0.118957
slack	0.097260	0.012484
completion_bias	0.059722	-0.059722
bottleneck_feed	0.014374	-0.003052

Statistical reproducibility notes

- The same random seed is used across policies within each instance-scenario-replication cell.
- Test instances MK04 and MK05 are not used during coefficient search or model selection.
- Wilcoxon tests are one-sided because superiority hypotheses were prespecified before the held-out comparisons.
- Benjamini-Hochberg correction is applied across all 16 planned comparisons.
- Bootstrap confidence intervals use 10,000 resamples of paired throughput differences with seed 20260801.
- The ablation experiment uses a separate seed family from the main held-out evaluation.