

Supplementary Information: Reliability-Aware Compact AI Framework for Industrial Predictive Maintenance Under Deployment Constraints

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Abstract

This supplementary file supports the reliability-aware compact artificial intelligence (AI) framework for predictive maintenance (PdM) by documenting pair-level Integrated Gradients (IG) artefacts, validation-status records, supplementary tables, data-array references, and visual evidence. It does not introduce new experiments, retraining runs, or additional metric claims. Its purpose is to make the main-paper framework comparison transparent, traceable, and auditable for reviewers.

Keywords: predictive maintenance, supplementary material, validation, Integrated Gradients, reliability-aware artificial intelligence

S1 Relationship to the main manuscript

The main manuscript reports a nine-family reliability-aware framework across AI4I and MetroPT. This supplementary file provides the detailed artefact layer behind that framework. It follows the same evidence logic as the revised Methodology and Results sections: model-registry scope, train/test evidence boundaries, reliability and perturbation records, IG summaries, and supplementary artefact traceability.

The supplementary material should be read as an audit companion. The main paper explains the framework-level interpretation, including why strong clean-condition ranking is not sufficient without calibration, latency, perturbation, and attribution evidence. This file retains the pair-level tables, figures, validation records, and data-array references that allow reviewers to inspect the basis for that interpretation.

Reproducibility-package boundary.

The accompanying Code Ocean capsule for this reliability-aware compact AI framework study is available at <https://codeocean.com/capsule/8855575/tree/v1>. The capsule is specific to the broader nine-family reliability-aware compact AI framework, although it shares some utility code and validation conventions with the companion NoiseGate project because both studies use the same public datasets and reproducibility infrastructure. The capsule is intended as a reviewer-facing reproducibility and source-code validation package. The default execution performs a lightweight smoke test that verifies environment setup, data-loading interfaces, model construction, training-loop execution, and result-export pathways. Complete manuscript-level results, figures, tables, and supplementary artefacts are reported in the manuscript and Supplementary Information. Full dataset-dependent reruns require restoring the complete public datasets according to the documented paths and disabling smoke-test mode. This capsule supports transparent review but should not be interpreted as a guarantee that every final figure and table is regenerated by the default run.

S2 Reviewer map

S3 Supplementary methodology notes

The reliability-aware framework was designed to compare compact model families under a shared evidence boundary. The supplementary material clarifies this boundary by retaining the pair-level IG tables and validation records rather than relying only on aggregate plots. This is important because the main paper argues that model quality is multi-dimensional: a model can rank well under clean conditions and still become less reliable under feature dropout or stronger perturbation.

The supplementary evidence also clarifies the role of the physics-guided gated variants. The magnitude-aware gate is a lightweight inductive-bias mechanism rather than a full physics-constrained solver. The pair-level tables and figures therefore support a careful interpretation: gated variants can be competitive and inspectable, but their value depends on the dataset, metric, and perturbation condition.

S4 Rendered supplementary tables

The following tables are rendered from the supplementary CSV sources retained in the clean release. They provide pair-level IG values and validation-status information that support the condensed attribution and reliability discussion in the main manuscript.

Table S1 How the supplementary material supports the reliability-aware framework manuscript.

Main-manuscript topic	Supplementary support	Interpretation boundary
Nine-model framework scope	Validation-status and pair-level supplementary tables	Confirms the validated model-dataset pairs without adding unreported models.
IG method	Pair-level attribution tables, visual artefacts, and data-array references	Supports attribution inspection, but does not establish causal physical mechanisms.
Reliability and perturbation discussion	Validation and repair-status logs	Helps distinguish clean-condition evidence from perturbation and fallback-local evidence.
Gated and ablation interpretation	Pair-level model summaries and visual artefacts	Supports cautious discussion of physics-guided gated and ablation variants.
Reproducibility package	Manifest, smoke-test, validation, and data-array listings	Documents the artefact package available to reviewers.

Table S2 Supplementary table S1: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
torque_nm	0.1512	0.1430
type_M	0.1328	-0.1328
phys_power_proxy	0.1156	0.1148
tool_wear_min	0.0386	0.0311
process_temperature_k	0.0351	0.0122
phys_thermo_mech	0.0338	0.0313
type_L	0.0331	-0.0292
air_temperature_k	0.0298	-0.0251
rotational_speed_rpm	0.0263	-0.0255
phys_delta_temp	0.0122	0.0122

Rendered from the copied supplementary CSV source retained with this project.

Table S3 Supplementary table S2: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
tp2	0.0155	0.0101
phys_elec_therm	0.0132	0.0132
phys_pres_diff	0.0085	-0.0085
comp	0.0069	0.0019
tp3	0.0050	-0.0038
h1	0.0047	-0.0047
mpg	0.0043	-0.0043
dv_electric	0.0040	-0.0040
reservoirs	0.0036	-0.0036
oil_temperature	0.0036	0.0017
motor_current	0.0035	-0.0031
oil_level	0.0023	0.0007
dv_pressure	0.0020	-0.0020
phys_dv_inter	0.0018	-0.0015
caudal_impulses	0.0012	-0.0012
lps	0.0006	-0.0006
towers	0.0004	-0.0004
pressure_switch	0.0004	-0.0003

Rendered from the copied supplementary CSV source retained with this project.

Table S4 Supplementary table S3: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
torque_nm	0.0336	-0.0271
air_temperature_k	0.0318	-0.0117
type_L	0.0183	-0.0183
rotational_speed_rpm	0.0173	0.0156
process_temperature_k	0.0156	0.0011
tool_wear_min	0.0153	-0.0148
type_M	0.0089	-0.0089

Rendered from the copied supplementary CSV source retained with this project.

Table S5 Supplementary table S4: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
motor_current	0.0438	-0.0279
reservoirs	0.0326	-0.0058
tp3	0.0320	-0.0082
tp2	0.0255	-0.0061
oil_level	0.0197	-0.0054
h1	0.0165	-0.0030
dv_electric	0.0155	-0.0029
caudal_impulses	0.0142	0.0068
oil_temperature	0.0119	-0.0100
dv_pressure	0.0100	-0.0100
comp	0.0073	-0.0072
mpg	0.0072	-0.0071
lps	0.0015	-0.0015
towers	0.0011	0.0006
pressure_switch	0.0008	-0.0002

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Table S6 Supplementary table S5: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
air_temperature_k	0.0381	-0.0350
tool_wear_min	0.0222	0.0115
process_temperature_k	0.0213	0.0200
rotational_speed_rpm	0.0169	0.0163
torque_nm	0.0166	-0.0033
type_L	0.0110	-0.0049
type_M	0.0089	-0.0050

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Table S7 Supplementary table S6: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
reservoirs	0.0369	-0.0202
motor_current	0.0268	-0.0085
tp2	0.0211	-0.0180
comp	0.0197	-0.0065
tp3	0.0160	-0.0007
h1	0.0157	0.0072
oil_level	0.0129	-0.0031
mpg	0.0111	-0.0009
dv_electric	0.0106	0.0008
caudal_impulses	0.0097	0.0057
oil_temperature	0.0088	0.0021
towers	0.0042	0.0042
dv_pressure	0.0039	0.0005
pressure_switch	0.0024	-0.0023
lps	0.0006	0.0003

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Table S8 Supplementary table S7: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
air_temperature_k	0.0098	-0.0026
type_M	0.0088	-0.0087
tool_wear_min	0.0078	-0.0078
torque_nm	0.0064	-0.0028
rotational_speed_rpm	0.0043	-0.0038
type_L	0.0040	0.0002
process_temperature_k	0.0036	0.0006

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Table S9 Supplementary table S8: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
oil_temperature	0.0209	0.0095
oil_level	0.0170	-0.0116
dv_electric	0.0156	-0.0115
caudal_impulses	0.0119	-0.0087
tp2	0.0094	0.0072
comp	0.0094	0.0075
reservoirs	0.0090	-0.0058
mpg	0.0065	-0.0044
motor_current	0.0054	-0.0026
tp3	0.0042	-0.0041
h1	0.0032	-8.85e-05
dv_pressure	0.0017	0.0013
pressure_switch	0.0012	0.0012
towers	0.0009	-0.0005
lps	0.0008	0.0008

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Table S10 Supplementary table S9: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
air_temperature_k	0.0222	0.0222
process_temperature_k	0.0215	-0.0010
type_L	0.0090	0.0070
type_M	0.0086	0.0086
rotational_speed_rpm	0.0079	0.0074
torque_nm	0.0050	0.0048
tool_wear_min	0.0042	0.0042

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Table S11 Supplementary table S10: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
comp	0.0297	-0.0259
tp3	0.0260	-0.0260
motor_current	0.0244	-0.0055
reservoirs	0.0183	0.0048
mpg	0.0180	-0.0180
dv_electric	0.0179	0.0121
oil_level	0.0178	-0.0134
oil_temperature	0.0178	-0.0050
caudal_impulses	0.0177	0.0060
tp2	0.0147	6.83e-05
h1	0.0145	0.0070
towers	0.0097	0.0097
dv_pressure	0.0053	-0.0035
pressure_switch	0.0017	0.0011
lps	0.0009	-0.0005

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Table S12 Supplementary table S11: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
torque_nm	0.0140	-0.0084
air_temperature_k	0.0132	0.0009
type_L	0.0108	-0.0002
tool_wear_min	0.0048	-3.09e-05
process_temperature_k	0.0043	-0.0027
type_M	0.0036	-0.0020
rotational_speed_rpm	0.0032	0.0023

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Table S13 Supplementary table S12: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
dv_electric	0.0164	-0.0137
mpg	0.0162	0.0082
reservoirs	0.0136	-0.0057
caudal_impulses	0.0117	-0.0054
tp2	0.0115	0.0042
oil_level	0.0098	0.0054
motor_current	0.0092	0.0062
tp3	0.0087	-0.0042
comp	0.0082	0.0020
h1	0.0071	-0.0044
oil_temperature	0.0067	0.0045
towers	0.0021	-0.0014
dv_pressure	0.0019	-0.0014
pressure_switch	0.0008	0.0004
lps	0.0007	0.0007

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Table S14 Supplementary table S13: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
type_L	0.0134	-0.0030
tool_wear_min	0.0061	0.0039
air_temperature_k	0.0055	0.0008
torque_nm	0.0054	-0.0002
type_M	0.0043	-0.0008
process_temperature_k	0.0039	-0.0023
rotational_speed_rpm	0.0023	-0.0022

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Table S15 Supplementary table S14: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
caudal_impulses	0.0262	0.0231
tp3	0.0146	0.0054
reservoirs	0.0126	0.0038
h1	0.0091	0.0081
oil_level	0.0084	0.0060
comp	0.0075	0.0029
motor_current	0.0058	0.0003
dv_electric	0.0047	-0.0005
mpg	0.0042	-0.0027
towers	0.0036	0.0020
oil_temperature	0.0034	-0.0005
tp2	0.0033	0.0007
dv_pressure	0.0017	0.0002
pressure_switch	0.0011	-0.0010
lps	0.0006	-0.0003

Rendered from the copied supplementary CSV source retained with this project.

Table S16 Supplementary table S15: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
air_temperature_k	0.0262	0.0143
torque_nm	0.0099	0.0092
tool_wear_min	0.0085	0.0029
process_temperature_k	0.0081	0.0079
type_L	0.0075	0.0058
type_M	0.0070	-0.0036
rotational_speed_rpm	0.0027	8.08e-05

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Table S17 Supplementary table S16: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
reservoirs	0.0159	0.0156
mpg	0.0133	0.0051
dv_electric	0.0126	0.0106
tp2	0.0115	0.0077
oil_level	0.0089	0.0075
oil_temperature	0.0074	-0.0065
h1	0.0061	-0.0017
tp3	0.0061	0.0049
motor_current	0.0050	-0.0013
towers	0.0035	0.0035
comp	0.0035	-0.0018
caudal_impulses	0.0027	0.0013
dv_pressure	0.0022	-0.0001
pressure_switch	0.0010	0.0007
lps	0.0006	0.0006

Rendered from the copied supplementary CSV source retained with this project.

Table S18 Supplementary table S17: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
process_temperature_k	0.0362	-0.0362
torque_nm	0.0282	-0.0196
air_temperature_k	0.0209	-0.0179
tool_wear_min	0.0182	-0.0179
rotational_speed_rpm	0.0151	-0.0149
type_M	0.0117	0.0105
type_L	0.0064	-0.0005

Rendered from the copied supplementary CSV source retained with this project.

Table S19 Supplementary table S18: pair-level IG attribution

feat	mean_abs_ig	mean_signed_ig
reservoirs	0.0477	-0.0122
oil_level	0.0358	0.0112
motor_current	0.0205	-0.0205
h1	0.0173	-0.0173
tp3	0.0159	0.0043
caudal_impulses	0.0126	0.0001
mpg	0.0125	0.0019
dv_electric	0.0113	-0.0083
oil_temperature	0.0090	-0.0019
comp	0.0088	-0.0067
towers	0.0070	0.0066
dv_pressure	0.0060	-0.0060
tp2	0.0052	-0.0018
pressure_switch	0.0023	-0.0013
lps	0.0005	0.0002

Rendered from the copied supplementary CSV source retained with this project.

Table S20 Supplementary table S19: validation and repair status log

model	dataset	performance_status	reliability_status	interpretability_status
AE classifier Lite	A14I	imported_primary	fallback_local	imported
AE classifier Lite	MetroPT	imported_primary	fallback_local	imported
No-buffer ablation	A14I	fallback_local	fallback_local	computed_fallback
No-buffer ablation	MetroPT	fallback_local	fallback_local	imported_fallback_run
No-gate ablation	A14I	imported_primary	fallback_local	imported
No-gate ablation	MetroPT	imported_primary	fallback_local	imported
BufferEnsemble PhysicsGate	A14I	imported_primary	fallback_local	imported
BufferEnsemble PhysicsGate	MetroPT	imported_primary	fallback_local	imported
PhysicsCrossGate ResMLP	A14I	imported_primary	fallback_local	imported
PhysicsCrossGate ResMLP	MetroPT	imported_primary	fallback_local	imported
PhysicsGate AE classifier	A14I	imported_primary	fallback_local	imported
PhysicsGate AE classifier	MetroPT	imported_primary	fallback_local	imported
PhysicsGate MLP	A14I	imported_primary	fallback_local	imported
PhysicsGate MLP	MetroPT	imported_primary	fallback_local	imported

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Table S21 Supplementary table S20: validation status

model	dataset	performance_status	reliability_status	interpretability_status
AE classifier Lite	AI4I	imported_primary	fallback_local	imported
AE classifier Lite	MetroPT	imported_primary	fallback_local	imported
No-buffer ablation	AI4I	fallback_local	fallback_local	computed_fallback
No-buffer ablation	MetroPT	fallback_local	fallback_local	imported_fallback_run
No-gate ablation	AI4I	imported_primary	fallback_local	imported
No-gate ablation	MetroPT	imported_primary	fallback_local	imported
BufferEnsemble PhysicsGate	AI4I	imported_primary	fallback_local	imported
BufferEnsemble PhysicsGate	MetroPT	imported_primary	fallback_local	imported
GRU Lite	AI4I	imported_primary	imported_primary_+ plus_local	imported
GRU Lite	MetroPT	imported_primary	imported_primary_+ plus_local	imported
PhysicsCrossGate ResMLP	AI4I	imported_primary	fallback_local	imported
PhysicsCrossGate ResMLP	MetroPT	imported_primary	fallback_local	imported
PhysicsGate AE classifier	AI4I	imported_primary	fallback_local	imported
PhysicsGate AE classifier	MetroPT	imported_primary	fallback_local	imported
PhysicsGate MLP	AI4I	imported_primary	fallback_local	imported
PhysicsGate MLP	MetroPT	imported_primary	fallback_local	imported
ResMLP Lite	AI4I	imported_primary	imported_primary_+ plus_local	imported
ResMLP Lite	MetroPT	imported_primary	imported_primary_+ plus_local	imported

Rendered from the copied supplementary CSV source retained with this project.

S5 Supplementary visual artefacts

The following figures reproduce the uploaded pair-level IG visual artefacts retained in `supplementary_assets/figures/`. They are included to make the attribution-supported framework discussion inspectable. The numerical attribution values are reported in Tables [S2–S19](#), and the validation status is reported in Tables [S20–S21](#).



Fig. S1 Supplementary pair-level IG visual artefact 1. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.



Fig. S2 Supplementary pair-level IG visual artefact 2. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.



Fig. S3 Supplementary pair-level IG visual artefact 3. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.

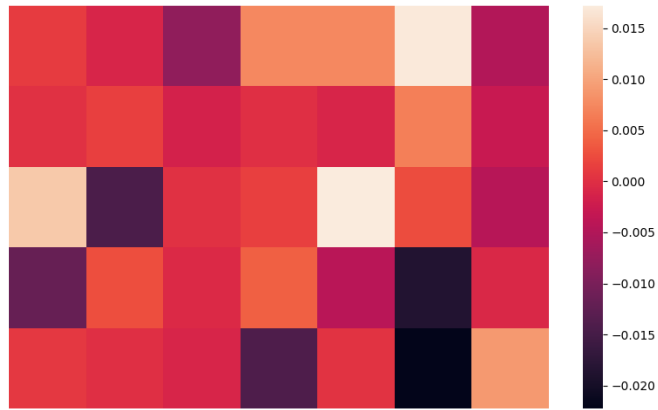


Fig. S4 Supplementary pair-level IG visual artefact 4. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.



Fig. S5 Supplementary pair-level IG visual artefact 5. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.

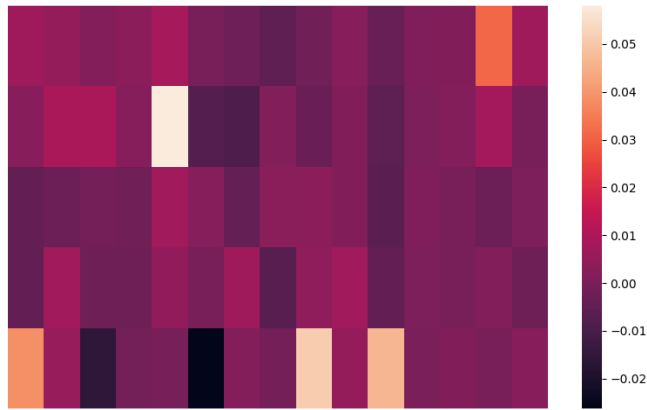


Fig. S6 Supplementary pair-level IG visual artefact 6. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.



Fig. S7 Supplementary pair-level IG visual artefact 7. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.



Fig. S8 Supplementary pair-level IG visual artefact 8. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.



Fig. S9 Supplementary pair-level IG visual artefact 9. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.



Fig. S10 Supplementary pair-level IG visual artefact 10. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.



Fig. S11 Supplementary pair-level IG visual artefact 11. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.



Fig. S12 Supplementary pair-level IG visual artefact 12. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.



Fig. S13 Supplementary pair-level IG visual artefact 13. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.



Fig. S14 Supplementary pair-level IG visual artefact 14. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.

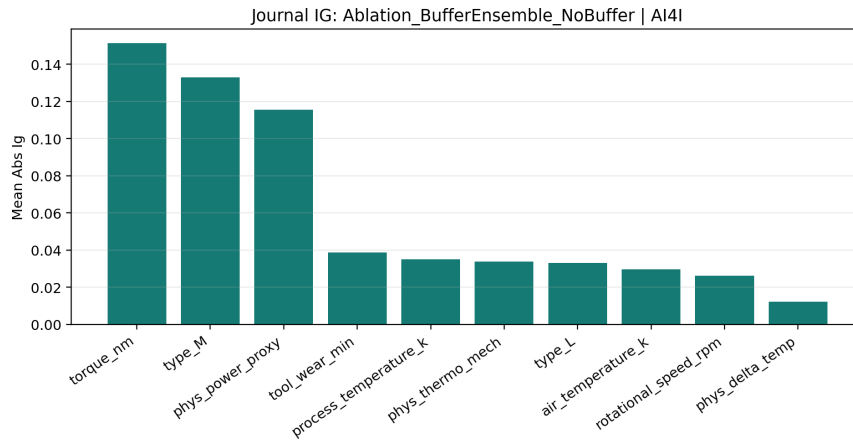


Fig. S15 Supplementary pair-level IG visual artefact 15. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.

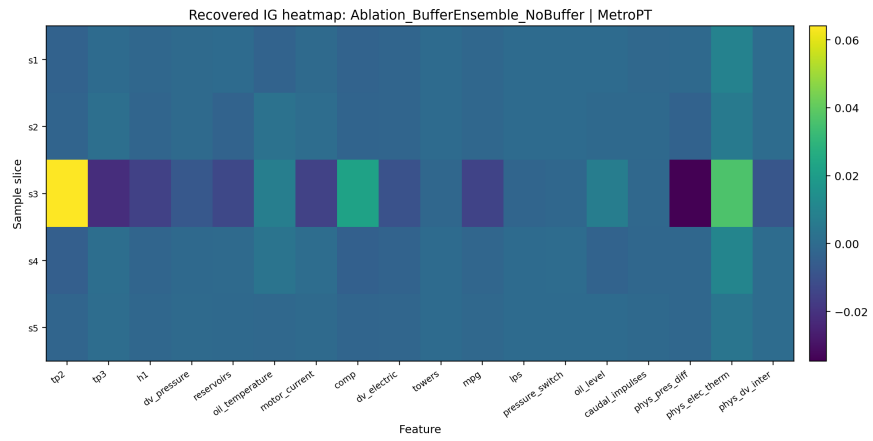


Fig. S16 Supplementary pair-level IG visual artefact 16. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.



Fig. S17 Supplementary pair-level IG visual artefact 17. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.

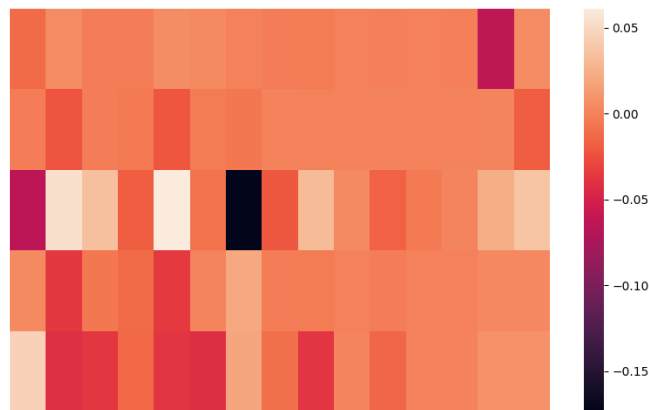


Fig. S18 Supplementary pair-level IG visual artefact 18. The corresponding pair-level numerical values are provided in the supplementary tables and validation records.

S6 Supplementary data arrays, validation files, and artefact trail

The following IG data arrays are included where present:

- supplementary_assets/data/journal_freeze_appendix_ig_data_No-bufferablation_AI4I.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_No-bufferablation_MetroPT.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_No-gateablation_AI4I.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_No-gateablation_MetroPT.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_AEclassifierLite_AI4I.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_AEclassifierLite_MetroPT.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_BufferEnsemblePhysicsGate_AI4I.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_BufferEnsemblePhysicsGate_MetroPT.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_GRULite_AI4I.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_GRULite_MetroPT.npy

- supplementary_assets/data/journal_freeze_appendix_ig_data_PhysicsCrossGateResMLP_AI4I.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_PhysicsCrossGateResMLP_MetroPT.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_PhysicsGateAEclassifier_AI4I.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_PhysicsGateAEclassifier_MetroPT.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_PhysicsGateMLP_AI4I.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_PhysicsGateMLP_MetroPT.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_ResMLPLite_AI4I.npy
- supplementary_assets/data/journal_freeze_appendix_ig_data_ResMLPLite_MetroPT.npy

The following validation files are included:

- supplementary_assets/validation/journal_freeze_smoke.txt
- supplementary_assets/validation/journal_freeze_validation_status.csv

If a separate manifest file is included in the submitted supplementary package, it should be read as an index to the same artefact trail rather than as an additional source of results. The validation files and data-array references listed above remain the primary supplementary records for the framework release.

S7 Scope of interpretation

The supplementary evidence supports the balanced interpretation used in the main paper. The framework shows that compact models can perform strongly, particularly on MetroPT, and that residual and recurrent baselines are important comparators. It also shows that perturbation sensitivity remains a meaningful limitation. The IG artefacts help make model behaviour inspectable, but they should be treated as supportive attribution evidence rather than causal proof. This interpretation keeps the framework optimistic, transparent, and appropriately bounded for journal review.