Explainable Predictive Maintenance in Steel Rolling

Jakub Jakubowski
AGH University of Science and Technology
ArcelorMittal Poland
27.03.2025

Main collaborators

This work was made possible with the support of my key collaborators

prof. dr hab. inż. Grzegorz J. Nalepa
Jagiellonian University

dr inż. Szymon Bobek
Jagiellonian University

dr inż. Przemysław Stanisz
ArcelorMittal Poland (formerly)

ArcelorMittal

Key dimensions of the reserach

Explainable Artificial Intelligence

Ensures transparency and interpretability of AI models, making their decisions understandable for stakeholders

Predictive Maintenance

Uses data-driven insights to anticipate equipment failures, reducing downtime and maintenance costs

Steel Rolling

One of the critical steel manufacturing steps, which requires high reliability and precision of the equipment

ArcelorMittal

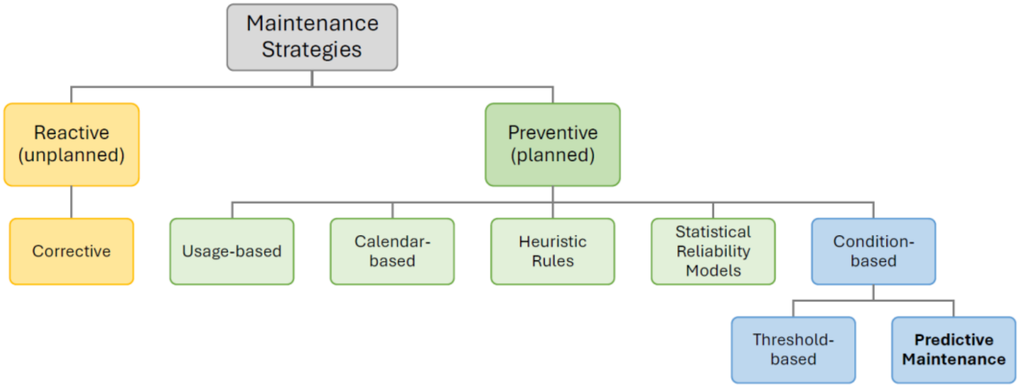
Predictive Maintenance

Objective: Predict failures before they occur (or soon after first symptoms) to minimize downtime and costs.

Data Sources: Sensor readings, operational logs, and historical failures.

Benefits:

- Reduces unexpected breakdowns.
- Optimizes maintenance schedules.
- Extends equipment lifespan.
- Improves production efficiency.



ArcelorMittal

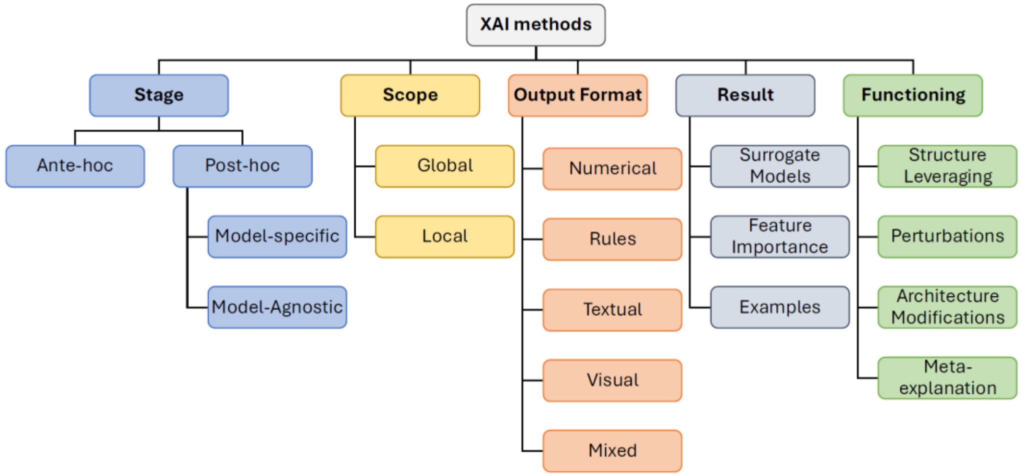
Explainable AI (XAI)

Why XAI in Predictive Maintenance?

- AI models in industry must be interpretable for engineers and decision-makers.
- Black-box models can be accurate but lack transparency, leading to trust issues.
- XAI helps understand why a model makes certain predictions, improving reliability and adoption.

Forms of XAI:

- Post-hoc Explainability (SHAP, LIME, Counterfactual Explanations)
- Intrinsic Explainability (Decision Trees, Linear Models)
- Local vs. Global Explanations



ArcelorMittal

Steel Rolling Process

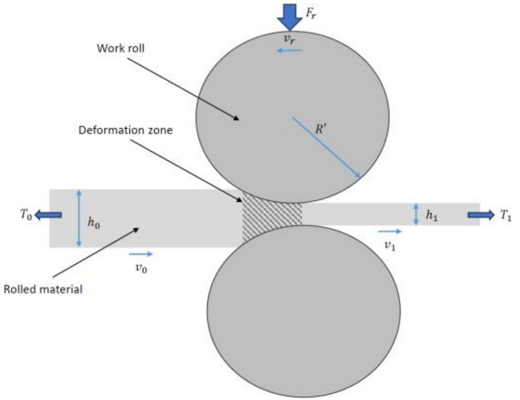
What is Steel Rolling? Steel rolling is a metal forming process where steel is passed through rollers to reduce thickness, improve mechanical properties, and achieve desired shapes.

Types of Steel Rolling:

- **Hot Rolling** - steel is heated above its recrystallization temperature (~1,100ºC) and then rolled.
- **Cold Rolling** - steel is rolled at or near room temperature after hot rolling.

Key process parameters:

- Strip thickness
- Rolling force and torque
- Rolling speed
- Strip tensions
- Reductions



Reasearch Problems

RP1: How to develop anomaly detection methods for rolling mills, which will address the problems of data imbalance, evolving data and limited availability of labeled data?

RP2: How to develop methods to predict the degradation of work rolls using the data recorded from the rolling process?

RP3: How to develop explainable predictive maintenance methods for rolling mills that are robust in operation and understandable to stakeholders?

Reasearch Tasks

T1: Conduct a comprehensive comparative study of existing ML-based PdM methods applied in steel industry.

T2: Investigate the characteristics of the data collected from the rolling process, specifically focusing on data imbalance, concept drift, and availability of labeled data, and prepare this data for use with ML models.

T3: Develop anomaly detection models for monitoring steel rolling processes.

T4: Develop ML models for prediction of work rolls degradation in the rolling process.

T5: Develop methods to provide transparent and interpretable explanations for the PdM models, ensuring their outputs are understandable to stakeholders.

Research Results

	Paper	Conference/Journal	MNiSW Points	Citations
P1	Explainable anomaly detection for hot rolling industrial process	DSAA 2021	140	30
P2	Anomaly detection in asset degradation process using variational autoencoder and explanations	Sensors	100	47
P3	Roll wear prediction in strip cold rolling with physics-informed autoencoder and counterfactual explanations	DSAA 2022	140	14
P4	Towards online anomaly detection in steel manufacturing process	ICCS 2023	140	3
P5	Explainable anomaly detection in industrial streams	ECAI 2023 Workshops	0	2
P6	Assessment of explainable anomaly detection for monitoring of cold rolling process	ICCS 2024	140	0
P7	Artificial intelligence approaches for predictive maintenance in the steel industry: A survey	To be submitted	0	5 (pre-print)
P8	Benchmark datasets for predictive maintenance challenges in steel manufacturing	Nature Scientific Data (in review)	0 / 140	-
			Total	**96**

ArcelorMittal

Research Results

	T1	T2	T3	T4	T5
P1		●	●		●
P2		●		●	●
P3		●		●	●
P4		●	●		
P5		●	●		●
P6		●	●		●
P7	●				
P8		●	●		

ArcelorMittal

Reserach Task 1

Conduct a comprehensive comparative study of existing ML-based PdM methods applied in steel industry

- What types of installation and equipment are analyzed?
- What AI methods are used?
- What types of PdM approaches are used?
- What are the characteristics of the data used?
- What is the business impact of the proposed methods?

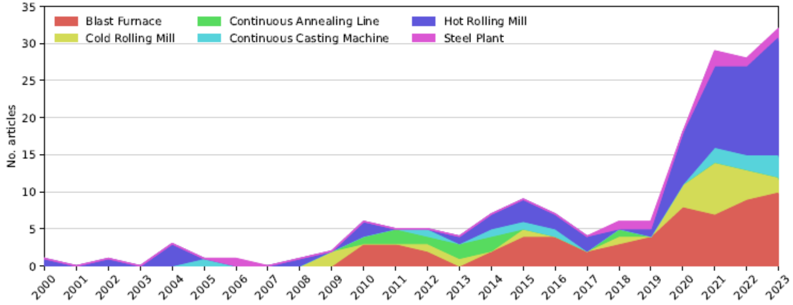
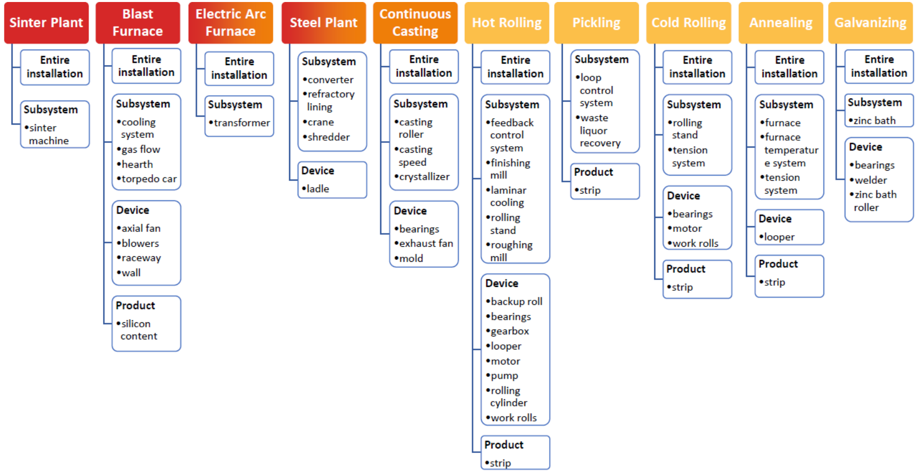


Figure 11: Historical distribution of installations subjected to predictive maintenance

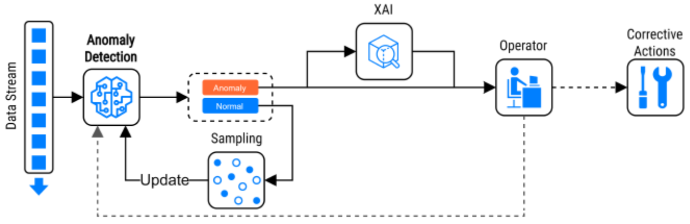


ArcelorMittal

Reserach Task 2

Investigate the characteristics of the data collected from the rolling process, specifically focusing on data imbalance, concept drift, and availability of labeled data, and prepare this data for use with ML models.

- Investigated multiple unsupervised anomaly detection models.
- Verified different strategies for dealing with concept drifts in the cold rolling process.
- Proposed online anomaly detection systems to handle concept drifts and imbalanced data.
- Created a simulation of the cold rolling process to build synthetic datasets for unbiased validation of anomaly detection models.



(a) Online anomaly detection.

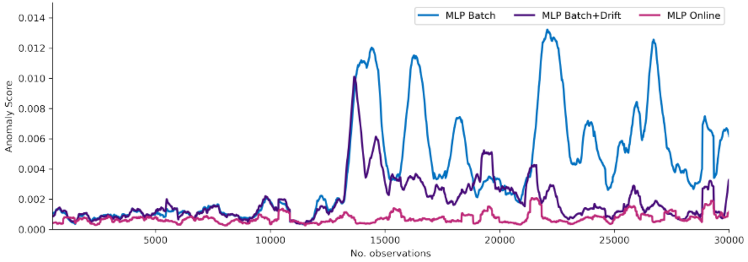


Figure 13: Evolution of anomaly score in monitoring of cold rolling process with different training approaches.

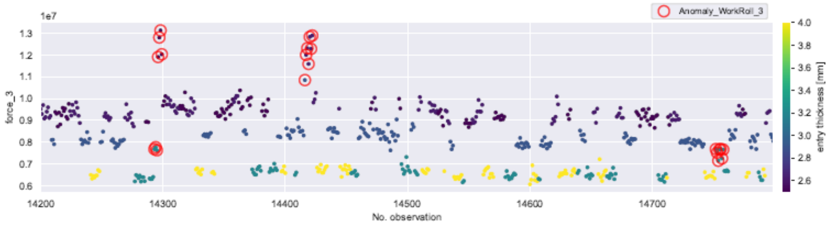
Reserach Task 3

Develop anomaly detection models for monitoring steel rolling processes.

- Compared a detailed comparison of the multiple anomaly detection models on the synthetic data from cold rolling process.
- Developed anomaly detection models, which consider the characteristics of rolling process to improve their prediction performance.
- Created six synthetic datasets, which can be used for the development of anomaly detecion methods

Model	PRAUC	F1	G-mean	Precision	Recall
SAE	0.74	0.67	0.81	0.69	0.66
AE	**0.81**	**0.75**	**0.86**	**0.76**	**0.74**
Half Space Trees	0.06	0.08	0.54	0.04	0.40
KMeans	0.27	0.28	0.52	0.29	0.28
Isolation Forest	0.39	0.35	0.58	0.37	0.34
LODA	0.36	0.32	0.60	0.28	0.37
Local Outlier Factor	0.60	0.55	0.67	0.71	0.45
One-Class SVM	0.44	0.40	0.65	0.37	0.43

Table 5: Performance of anomaly detection models on the synthetic data from cold rolling.

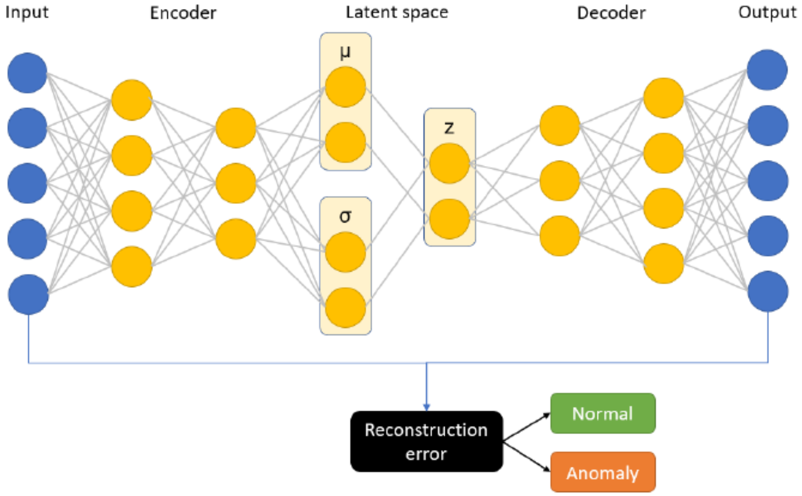


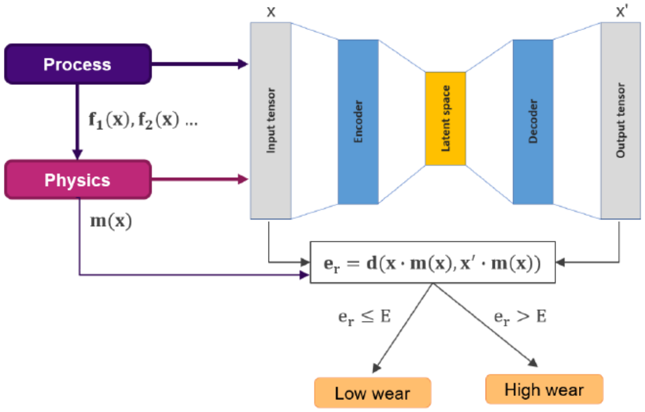
(a) Work roll anomalies.

Reserach Task 4

Develop ML models for prediction of work rolls degradation in the rolling process

- Developed a variational autoencoder for prediction of work roll wear in the hot rolling process.
- Developed a physics-informed autoencoder for prediction of roll wear in the cold rolling process, which utilized knowledge of mathematical equations describing the wear of the work rolls.



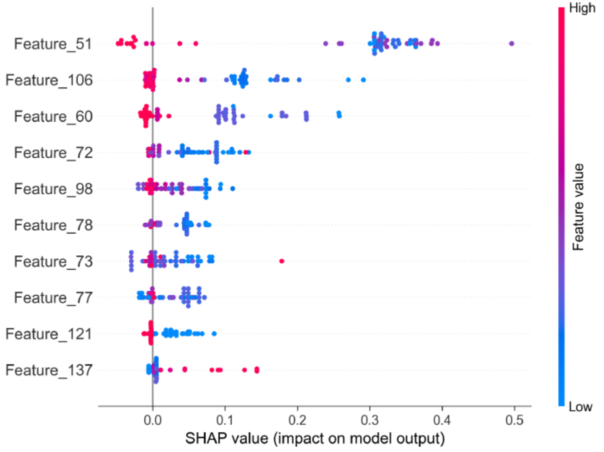


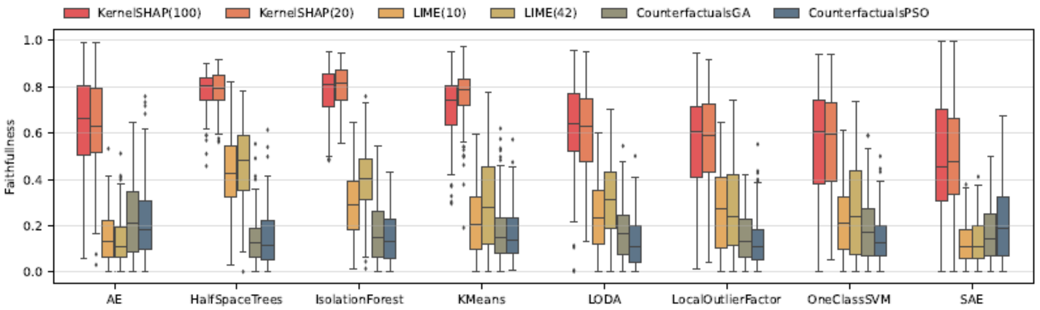
ArcelorMittal

Reserach Task 5

Develop methods to provide transparent and interpretable explanations for the PdM models, ensuring their outputs are understandable to stakeholders.

- Providing explanations to the anomaly detection and roll wear prediction models using various XAI methods.
- Evaluation of generated explanations taking into account their consistency with expert knowledge and usefullness in discovering root causes of anomalies.
- Examination of XAI performance for different anomaly detection models and XAI methods using selected metrics, i.e., faithfulness, stability, complexity and computational time.





ArcelorMittal

Summary of the research

- Conducted research that integrates Explainable AI, predictive maintenance, and the steel industry.
- Identified three distinct research problems and defined five research tasks.
- Developed models for anomaly detection and roll wear prediction in the steel rolling process.
- Provided explanations to these models using XAI methods to enhance their understandability and reliability.
- Co-authored eight papers that serve as the foundation of this thesis.
- The findings presented in the papers addressed the defined research problems outlined in the study, providing valuable insights and potential solutions.
- Potential directions of future research include:
  - development of deep learning models utilizing more complex architectures
  - using data from process simulation as a prior step to actual training (by applying transfer learning).
  - conducting more in-depth research on the understandability of explanations to end users.