



# DTMI 2025

International Workshop Carlo Longaretti  
on Digital Tools for the Metallurgical Industry

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DTMI\_019

# Framework with Digital Twins and Federated Learning for Decision Support in Multi-plant Schemes for Electric Steelmaking and Beyond

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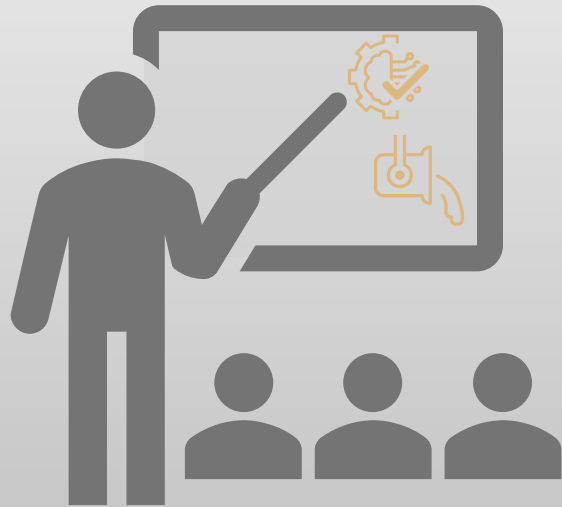


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## **ALCHIMIA project**

“Data and decentralized Artificial intelligence for a competitive and green European metallurgy industry”

Duration: 9/2022-11/2025 (39M)

Horizon Europe grant no. 101070046

<https://alchimia-project.eu/>

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## ALCHIMIA project themes



- (Steel production) process optimization with decision support



- Human factors



- Tools:
  - AI models
  - »Non-AI« models
  - Federated Learning, Continual Learning



- Life Cycle Assessment (LCA)



## Use cases

### Celsa

- Electric steelmaking route
- Case plants: France, Spain, Poland



### Fonderia di Torbole (FdT)

- Foundry; automotive components
- Case plant: Italy





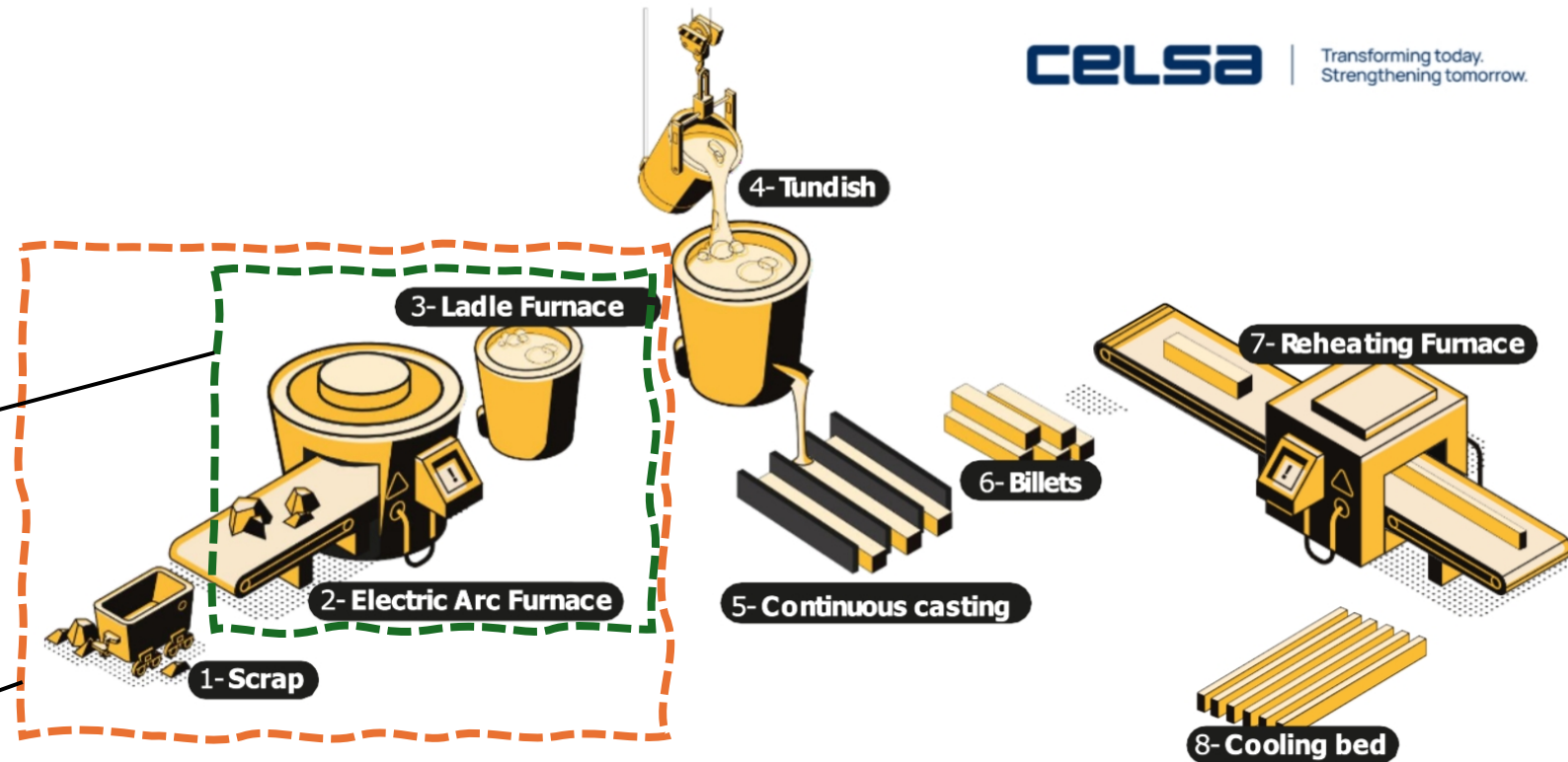
# Celsa: electric steelmaking route



This presentation



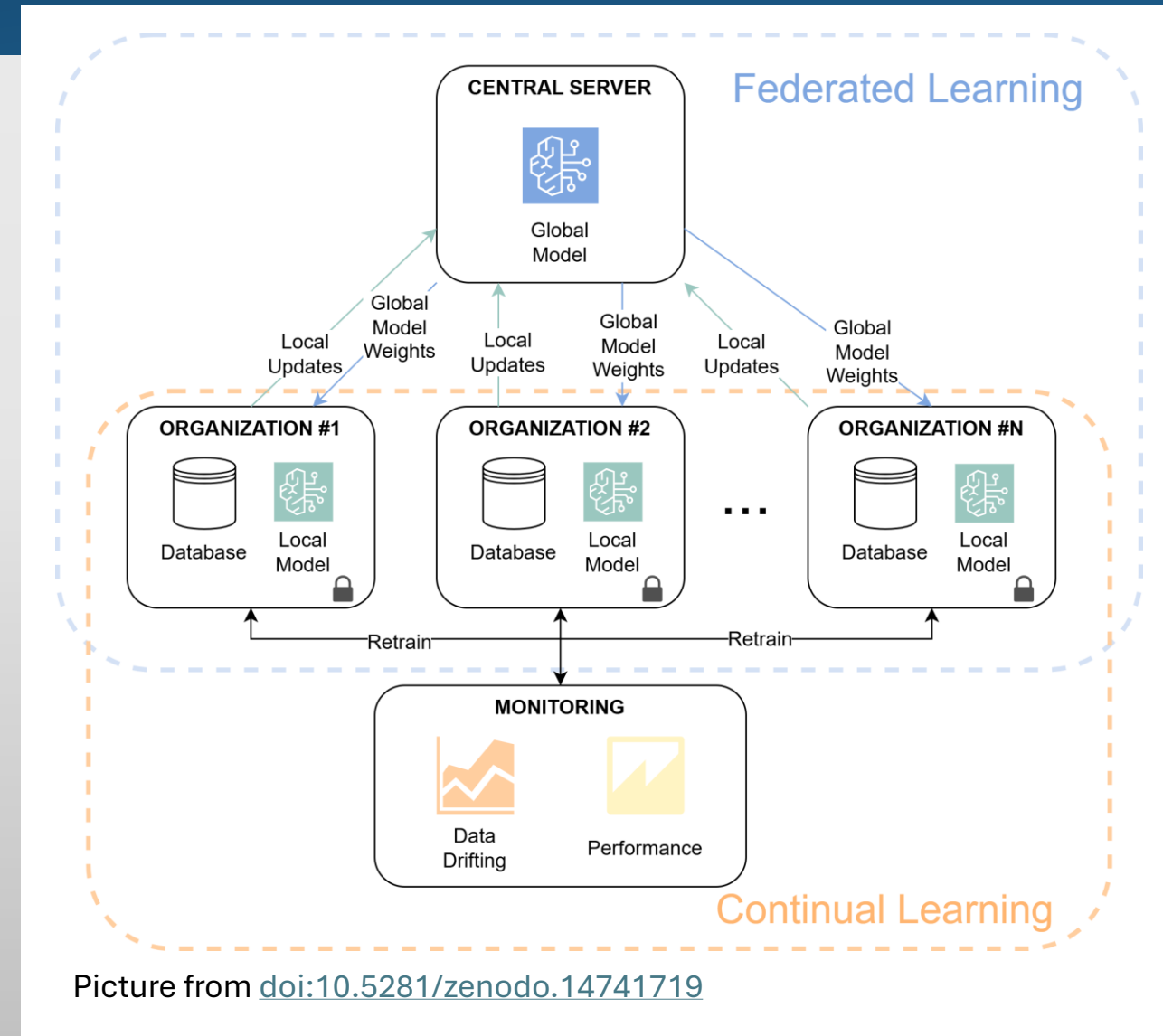
ALCHIMIA's  
Celsa use case





## Federated Learning and Continual Learning

- Federated Learning
  - Central server generates global model weights from local models
  - Local models not available to other local clients -> preserve privacy
- Continual Learning
  - Monitor model performance
  - Re-train model when appropriate

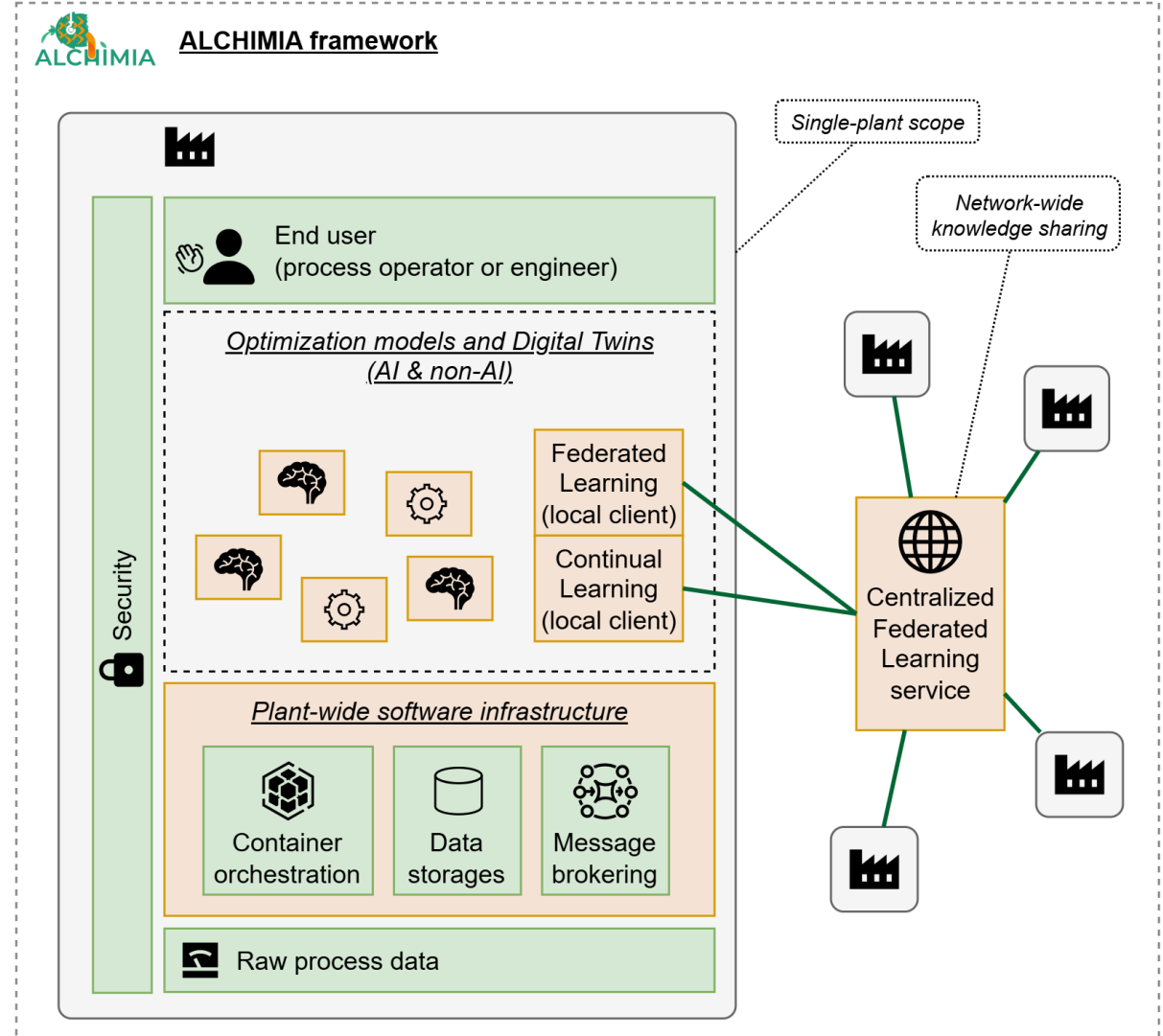


Picture from [doi:10.5281/zenodo.14741719](https://doi.org/10.5281/zenodo.14741719)



# ALCHIMIA framework

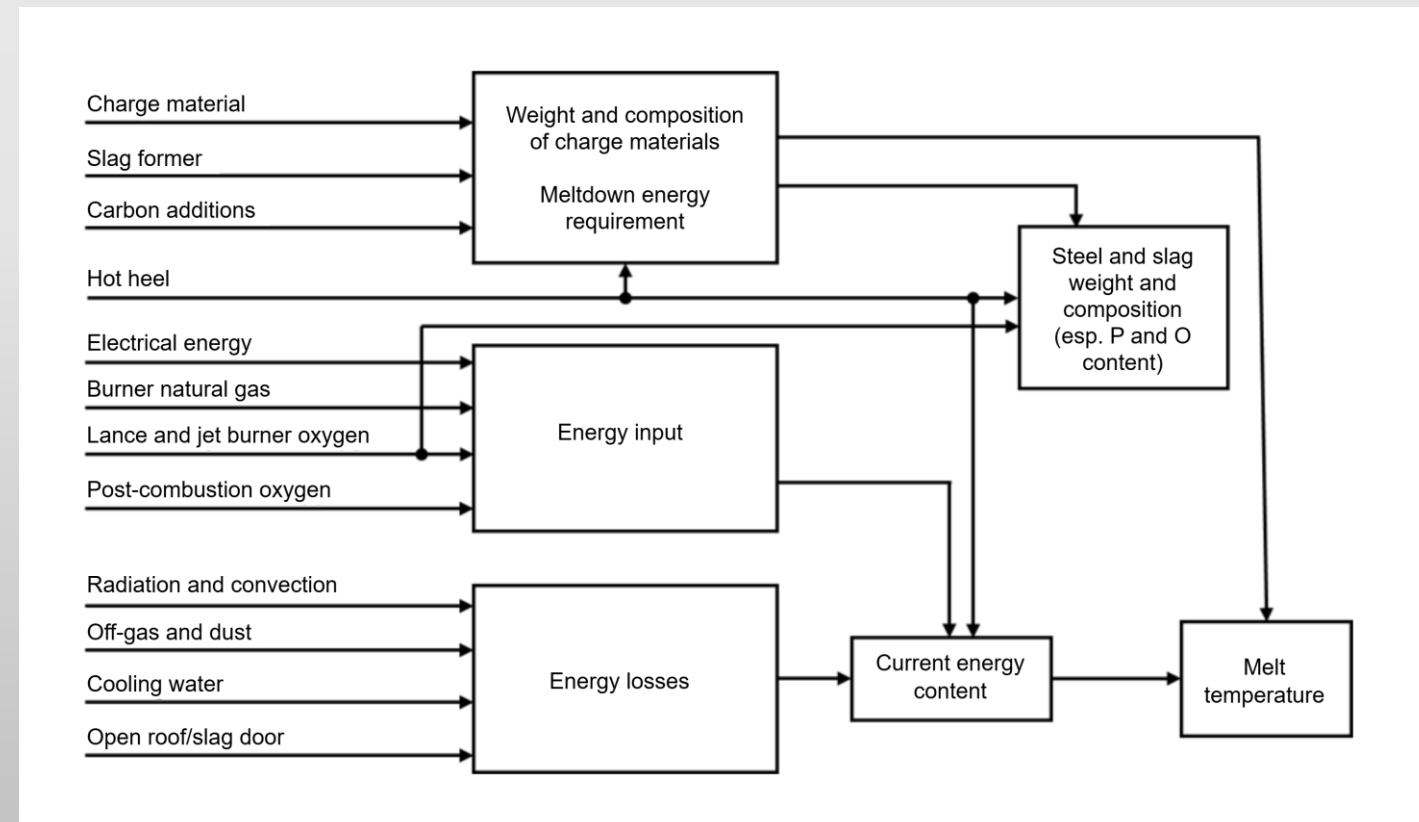
- Aiming at Federated Learning (FL) between production plants
  - Improve performance esp. if limited data coverage in some plant
- Each plant operates:
  - Its own optimization models
  - Its own data infrastructure
- Connectivity between plants and FL through the local client
- The models provide decision support to the operators/engineers
  - Human in the Loop





# Dynamic process model for Electric Arc Furnace (EAF)

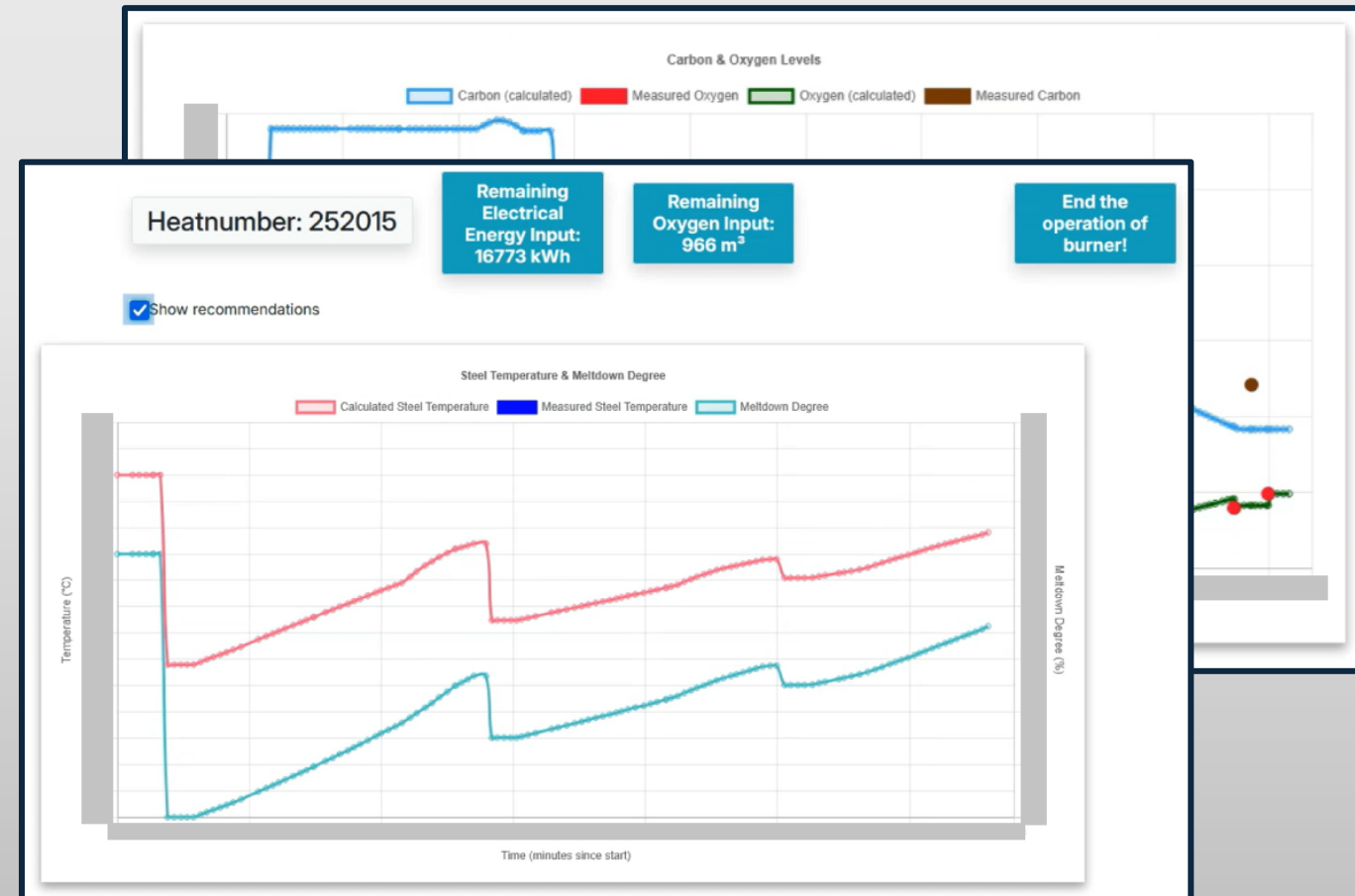
- Analytical/physical model based on equations
- Structured into submodels
  - Extensible
  - Accurate parametrization possible
- Online process monitoring:
  - melt temperature
  - meltdown degree
  - O, C and P content





# Dynamic process model for EAF

- Real-time decision support system
  - Human in the Loop
  - Digital Twin
- Adjustable set points
- Provides recommendations for:
  - Timing of:
    - basket charging
    - burner operation
  - Remaining amount of:
    - electrical energy
    - oxygen







# LF Optimization - Dashboard

Find component ...
Optimization Server [Logout](#)

Dashboard

Optimization

Run

Results

## Ladle Furnace

Heat number: **291240**

Steel weight: **144 tons**

Tapping temperature:  °C

### Current heat information

Heat	291240
Start date	2025-09-24 11:52
Quality	<input type="text"/>

HeatNumber	Quality	Date	SteelTemperature	Analysis
291228	<input type="text"/>	2025-08-14 08:36:17.73...	<input type="text"/>	<a href="#">VIEW</a>
291229	<input type="text"/>	2025-08-14 08:48:45.73...	<input type="text"/>	<a href="#">VIEW</a>
291230	<input type="text"/>	2025-08-14 14:42:56.32...	<input type="text"/>	<a href="#">VIEW</a>
291231	<input type="text"/>	2025-08-14 14:49:17.92...	<input type="text"/>	<a href="#">VIEW</a>

### Operator ferroalloys suggestions for heat number 291240

**Temperatures**

Minimum Steel Temperature [°]

Maximum Steel Temperature [°]

**Electrical Energy**

Electrical Energy Reference [MWh]  50

Electrical Energy Price [€/MWh]  15

**Argon**

Argon Consumption Reference [Nm<sup>3</sup>]  0.9

Argon Price [€/Nm<sup>3</sup>]  15

**Prices**

C Price [€/MWh]  300

CaO Price [€/MWh]  200

CaF<sub>2</sub> Price [€/MWh]  1500

CE30 Price [€/MWh]  350

FeS Price [€/MWh]  1200

FeV Price [€/MWh]  18000

MgO Price [€/MWh]  350

SiMn Price [€/MWh]  1200

**Impact categories**

[SELECT IMPACT CATEGORIES](#)

**Select material to add**

Material:

Quantity [kg]  Price [€]  Minimum value  Maximum value

[+ ADD](#)

[OPTIMIZE](#)

### Current heat information

Heat	291240
Start date	2025-09-24 11:52
Quality	<input type="text"/>
Temperature	<input type="text"/>
Weight	144T

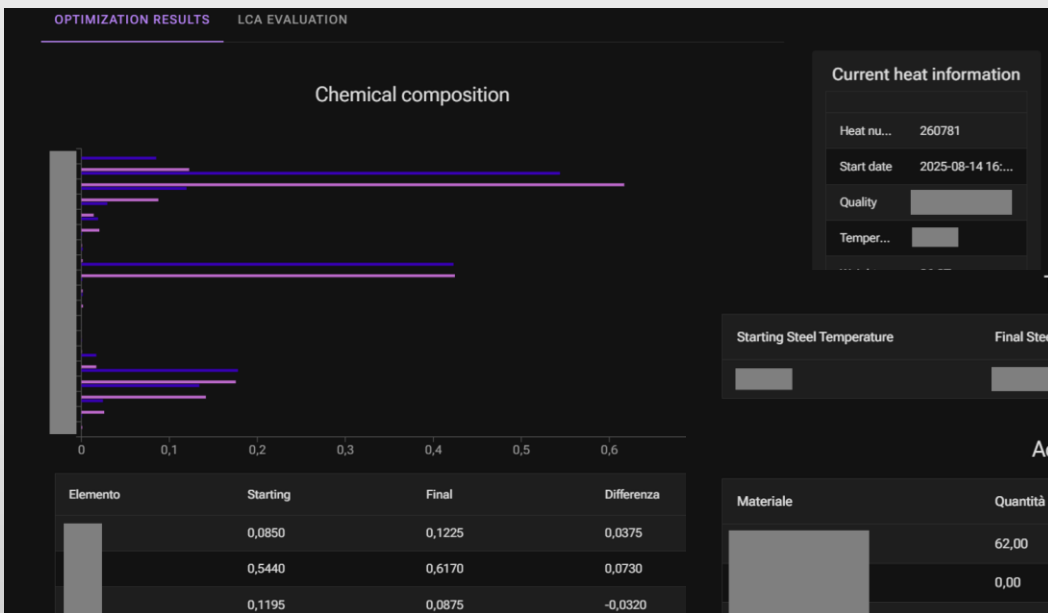
### Received data

Heat number	✓
Quality	✓
Temperature	✓
Weight	✓
Analysis	✓
Label	✗





# LF Optimization results + LCA evaluation:



### Temperatures

Starting Steel Temperature	Final Steel Temperature	Differenza
<input type="text"/>	<input type="text"/>	7,00

### Added materials

Materiale	Quantità	Unità di Misura
<input type="text"/>	62,00	kg
	0,00	kg
	0,00	kg
	40,00	kg
	0,00	kg
	8,00	kg
	0,00	kg
	0,00	kg
	182,00	kg
	309,00	kg

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OPTIMIZATION RESULTS   LCA EVALUATION

### Environmental Impact Evaluation

[EXPORT PDF](#)




Impact	Value	Unit of Measurement
Acidification	10,0000	mol H+ eq / kg
Climate change	0,4100	kg CO2 eq / kg
Climate change - Biogenic	0,2700	kg CO2 eq / kg
Climate change - Fossil	0,3800	kg CO2 eq / kg
Climate change - Land use and LU ch...	0,3900	kg CO2 eq / kg
Ecotoxicity, freshwater - part 1	66,2000	CTUe / kg
Ecotoxicity, freshwater - part 2	30,1000	CTUe / kg
Ecotoxicity, freshwater - inorganics	11,9000	CTUe / kg
Ecotoxicity, freshwater - organics - p.1	35,0000	CTUe / kg
Ecotoxicity, freshwater - organics - p.2	17,6000	CTUe / kg

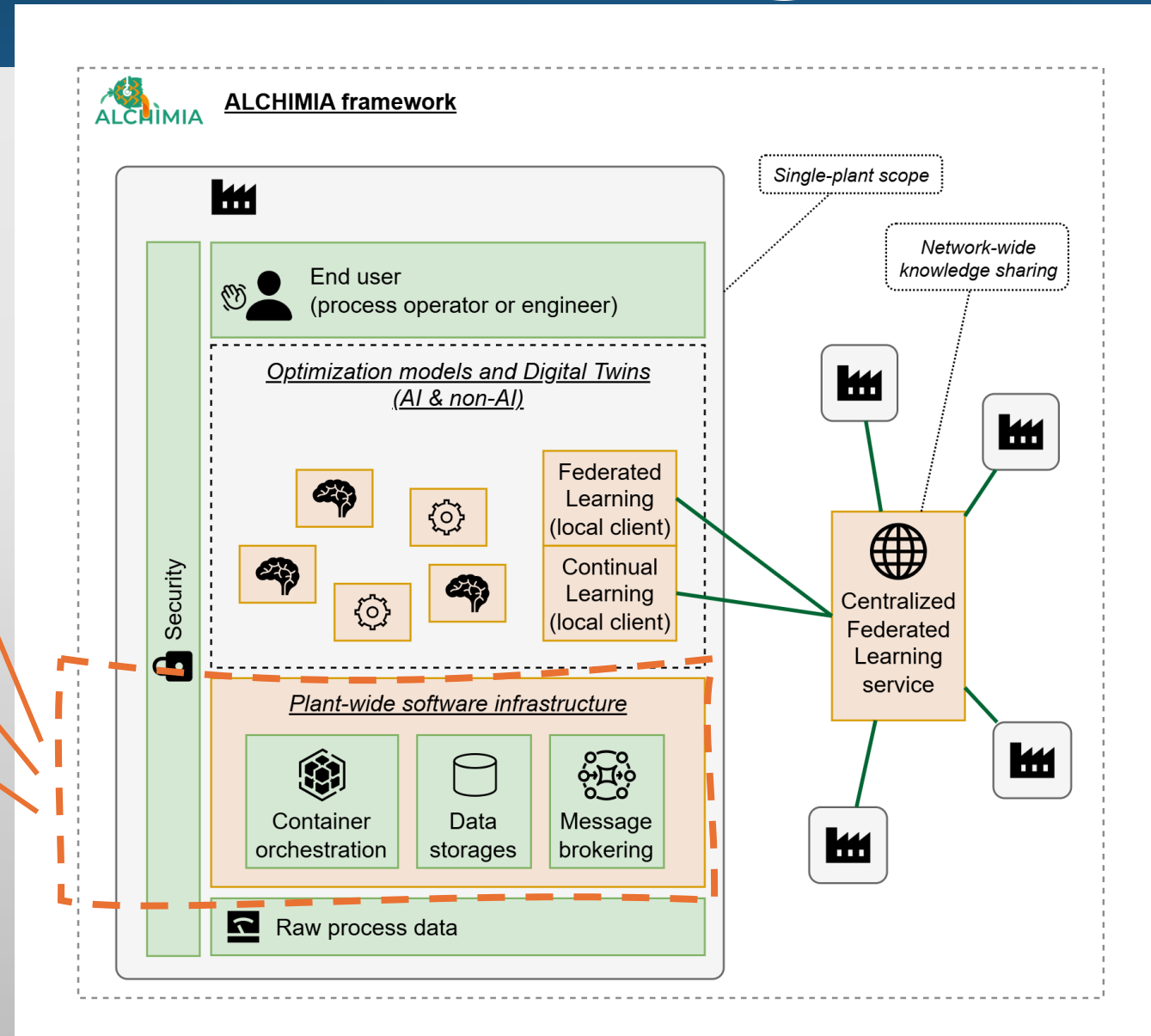
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## Software infrastructure

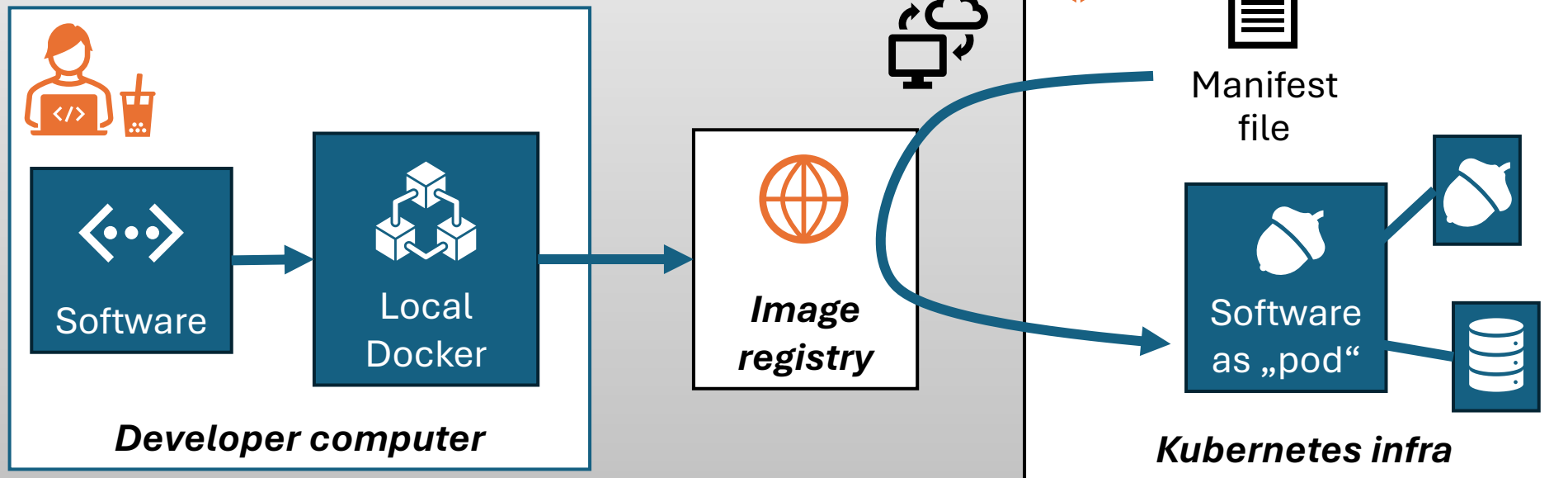
-  • Kubernetes for container orchestration
-  • Databases for historical data
-  • Message brokering with Apache Kafka





## Kubernetes

- “Infrastructure as Code” (IaC)
- Configure your system with manifest files; the infra installs components for you



```
kind: Deployment
volumes: ...
containers: ...
image: ...
---
kind: Service
...
---
kind: PersistentVolume
...
```

Manifest (YAML)



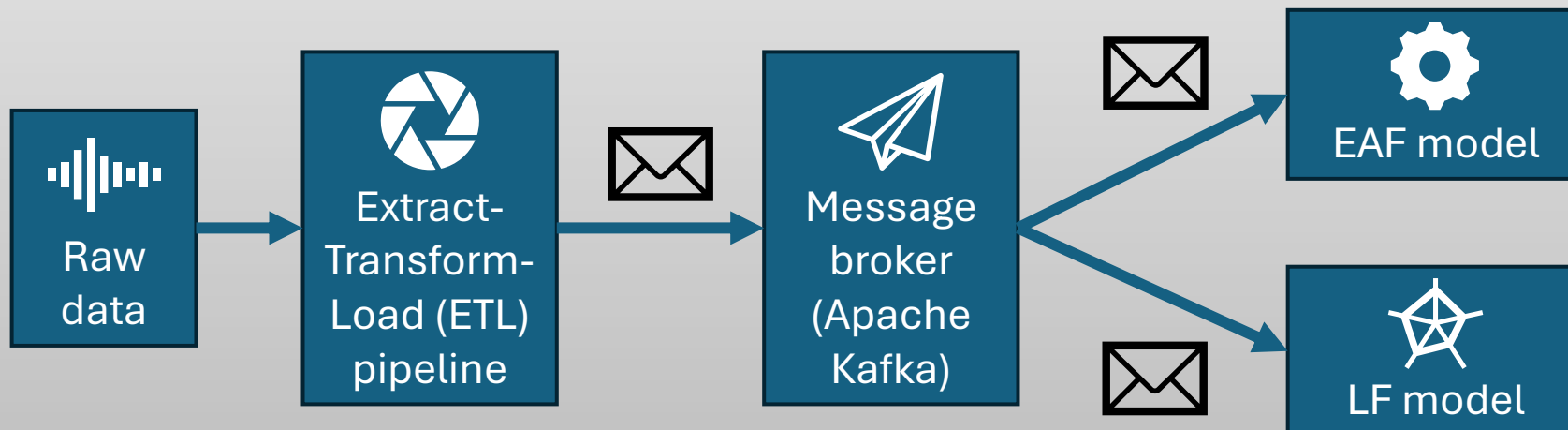
## Message-oriented communication

- Excels at event-based schemes
- We created “Smart Data Model” for common JSON structures
  - Open standard; <https://smartdatamodels.org>
  - Subject “IndustrialProcess” under domain “Smart Manufacturing”

```
{ "id": "urn:ngsi-ld:xxx",  
  "type": "ProcessChemicalAnalysis",  
  "dateObserved": "2025-07-17T14:07:00Z",  
  "processName": "eaf_1",  
  "heatNumber": 10021,  
  "chemicalAnalysis": {  
    "sampleNumber": 2,  
    "chemicalConcentration" : [  
      { "substance": "Fe", "percentage": 0.9873 },  
      { "substance": "Cu", "percentage": 0.0052 },  
      { "substance": "Mn", "percentage": 0.0023 }  
    ]  
  }  
}
```



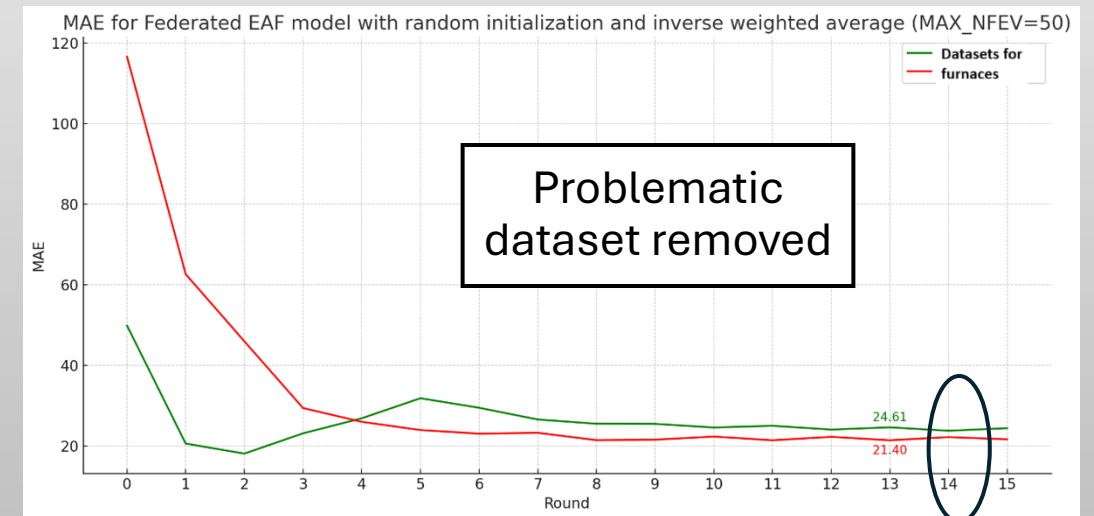
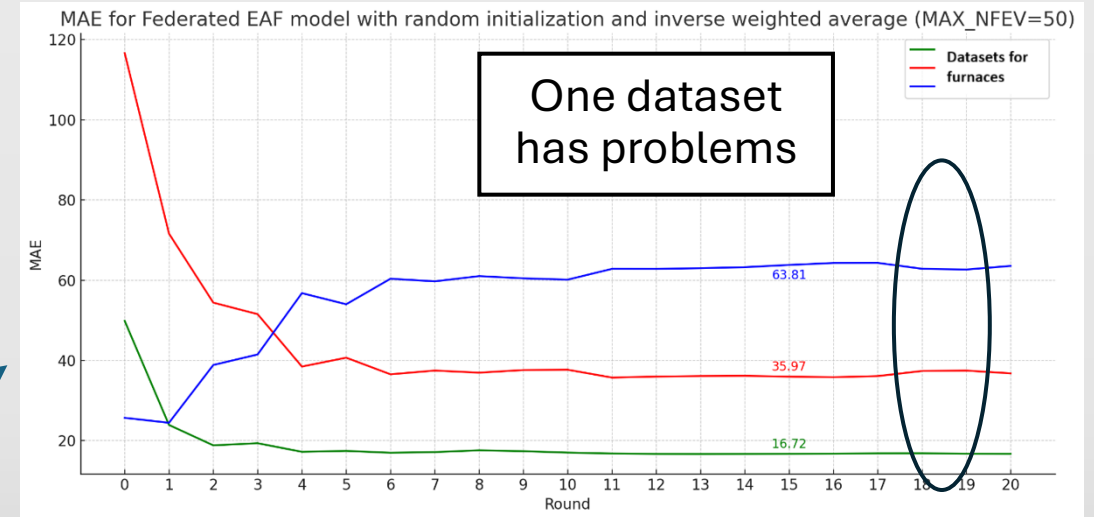
Example message





## Federated Learning results: EAF model (temperature; offline)

- How is Federated Learning possible here?
  - EAF model is physical/analytical, not AI!
  - Solution: apply FL to model-parametrization-related knowledge
- Seems to work, but the data must be OK
- Future work: fix the problematic dataset





## Federated Learning results: LF model (temperature; offline)

R2 score: regression performance  
MSE: Mean Squared Error

Model	Features	Plant 1		Plant 2		Plant 3	
		R2 Score	MSE	R2 Score	MSE	R2 Score	MSE
Local	FinalTemperature	0,278	137,33	0,580	36,65	0,158	59,10
Federated	FinalTemperature	0,446	98,88	0,579	45,56	0,299	32,77

- Plants 1 and 3: improvement in both R2 and MSE
  - Plant 1: smallest dataset
  - Plant 3: worst data quality; largest dataset
- Plant 2 results are maintained, especially R2
  - Possible reason: imbalanced datasets
- Conclusion: FL likely improves results
- Future experiments
  - Compensate imbalance in datasets
  - Discard bad data points



## Lessons learned



- Kubernetes
  - Infrastructure as Code -> reduce manual pain (however, someone must install + maintain it)
  - Requires some learning
  - Sometimes surprisingly primitive wrt. Docker



- Federated Learning
  - Lots of potential
  - More plants -> more challenges
    - Data quality, availability and symmetry?
  - Last step in chain -> will suffer if problems elsewhere



- Event-based communication
  - Important: functional interoperability: \*what\* happens \*when\*
  - Any message missing -> cannot calculate





## Conclusions

- Digital Twin framework reached its goals
  - Data integration
  - Decision support online
  - Federated Learning
- Federated Learning has potential in process industry
  - Promising results reached (offline in this presentation)
  - Data must be first-class citizen
- Develop concepts further in future projects





# Thank you for your attention!



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