Digital transformation of the steelmaking industry: An EAF case study

V. Logar, S. Tomažič, G. Andonovski, A. Blažič, I. Škrjanc

Faculty of electrical engineering, University of Ljubljana, Slovenia

4th EASES Symposium, 16. – 18. 6. 2021, IOB RWTH Aachen

Presentation overview

- EU Horizon 2020 project INEVITABLE (Optimization and performance improving in metal industry by digital technologies)
- EAF digitalization Use Case
- digital EAF solutions
  - mathematical EAF models
  - data-driven EAF models
  - EAF optimization concept
- digital infrastructure and integration of the solutions to industrial environment
- conclusions and further work

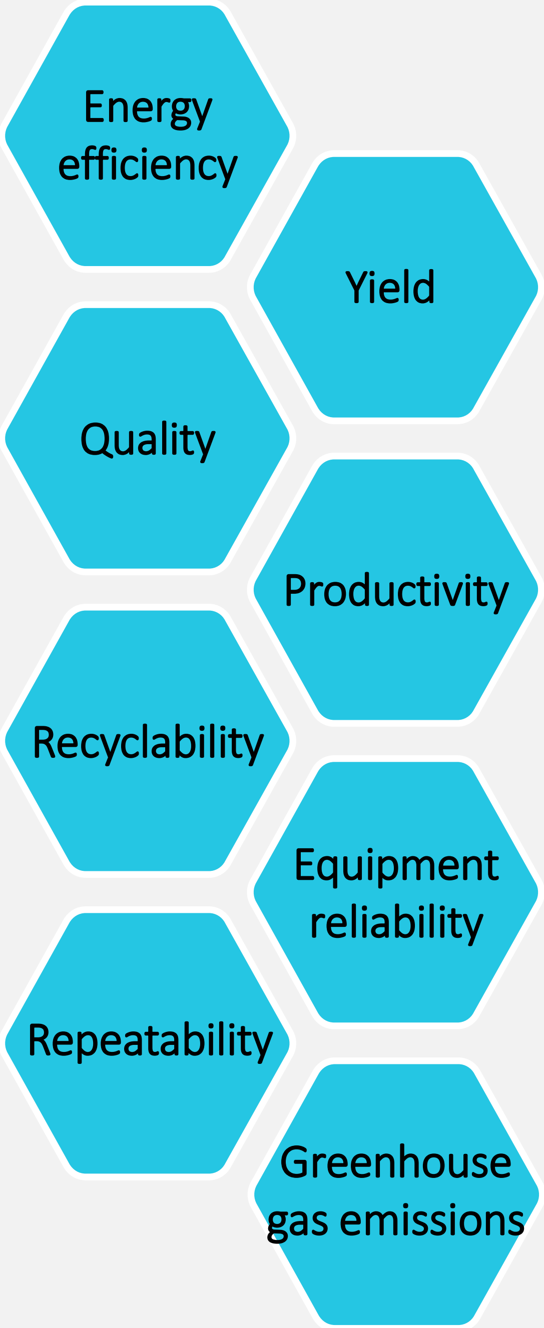
EU Horizon 2020 project **INEVITABLE**

Challenge

Improve the key performance indicators (KPIs) in steel and non-ferrous metal sectors by retrofitting existing production sites by digitalization and innovative high-level supervisory control technologies

- Duration: **1. 10. 2019 – 31. 3. 2023** (6-month extension due to Covid-19)
- Pursued goals:
  - increased process efficiency, equipment reliability, productivity, repeatability
  - increased product quality, recyclability, yield
  - reduced greenhouse gas emissions

http://inevitable-project.eu/



EU Horizon 2020 project **INEVITABLE**

Ambition

Improve the digitalization level of European steel and non-ferrous industry:

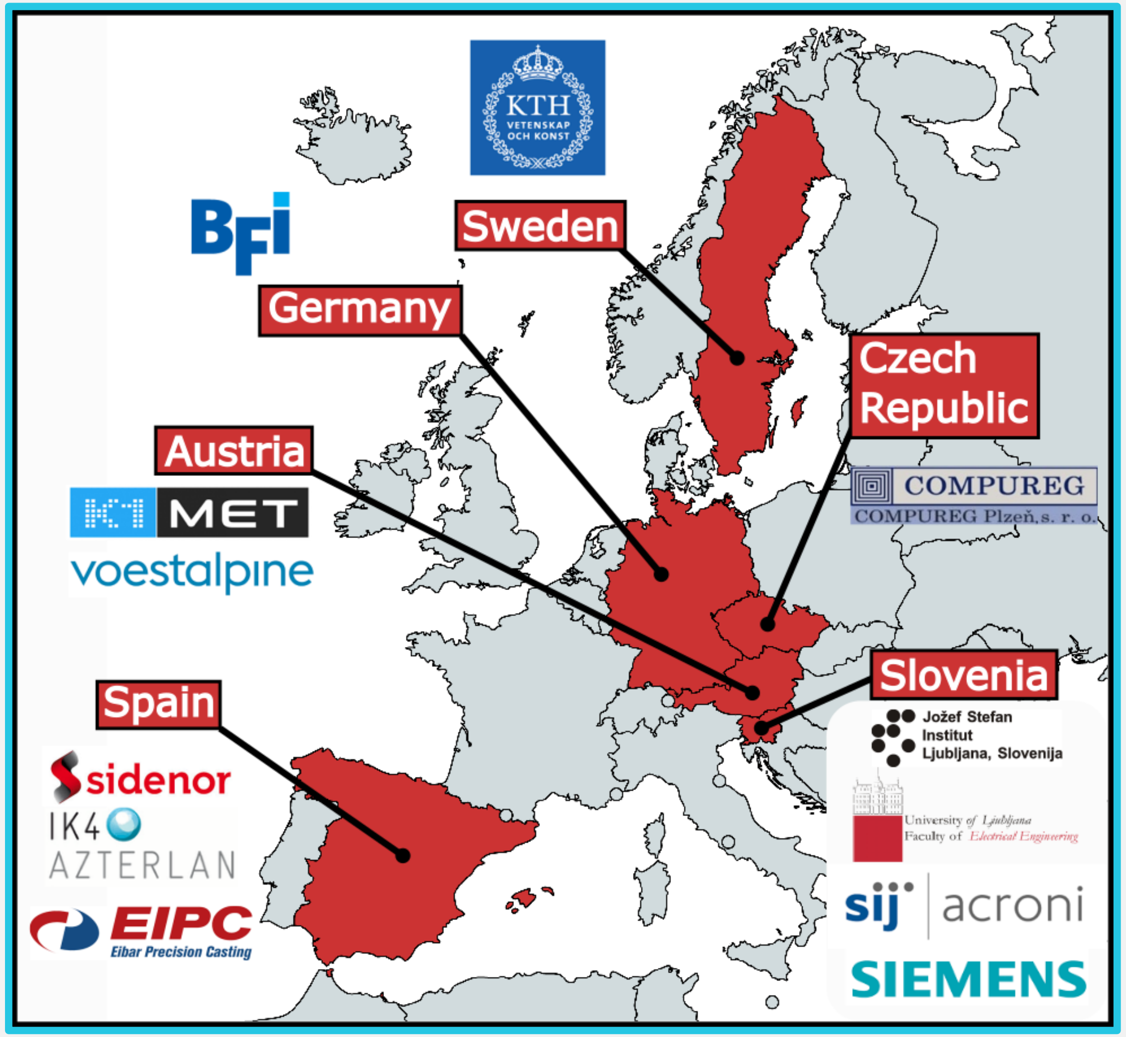
- modernize high value equipment through digital retrofitting,
- control and instrumentation equipment upgrade to enable plant-wide data collection,
- set up a design principle for digitalization infrastructure (IT-OT connectivity).

Steps towards cognitive production process:

- exceed the level and functionality of traditional process automation and control systems,
- extract and utilize the knowledge from data,
- combination of first principle modelling and advanced data analytics,
- digital twins, soft sensors, decision support systems, supervisory predictive control, and scheduling.

EU Horizon 2020 project **INEVITABLE**

Consortium



4 metallurgical institutions

4 industrial end users

4 control and automation specialists

EU Horizon 2020 project **INEVITABLE**

Concept

Develop and provide the digitalization enabling technologies:

- data collection & sensor technologies,
- tools for data analysis, control and optimization,
- digitalization infrastructure.

Demonstrate, test and evaluate the developed technologies using three selected use cases and different processes:

- Use Case 1: EAF, ZRM (SIJ Acroni, Slovenia)
- Use Case 2: LD, VD, CC (Sidenor- Spain, Voestalpine - Austria)
- Use Case 3: non-ferrous alloy casting (EIPC – Spain)

sij | acroni
voestalpine ONE STEP AHEAD.
sidenor
EIPC Eibar Precision Casting

EAF digitalization use case

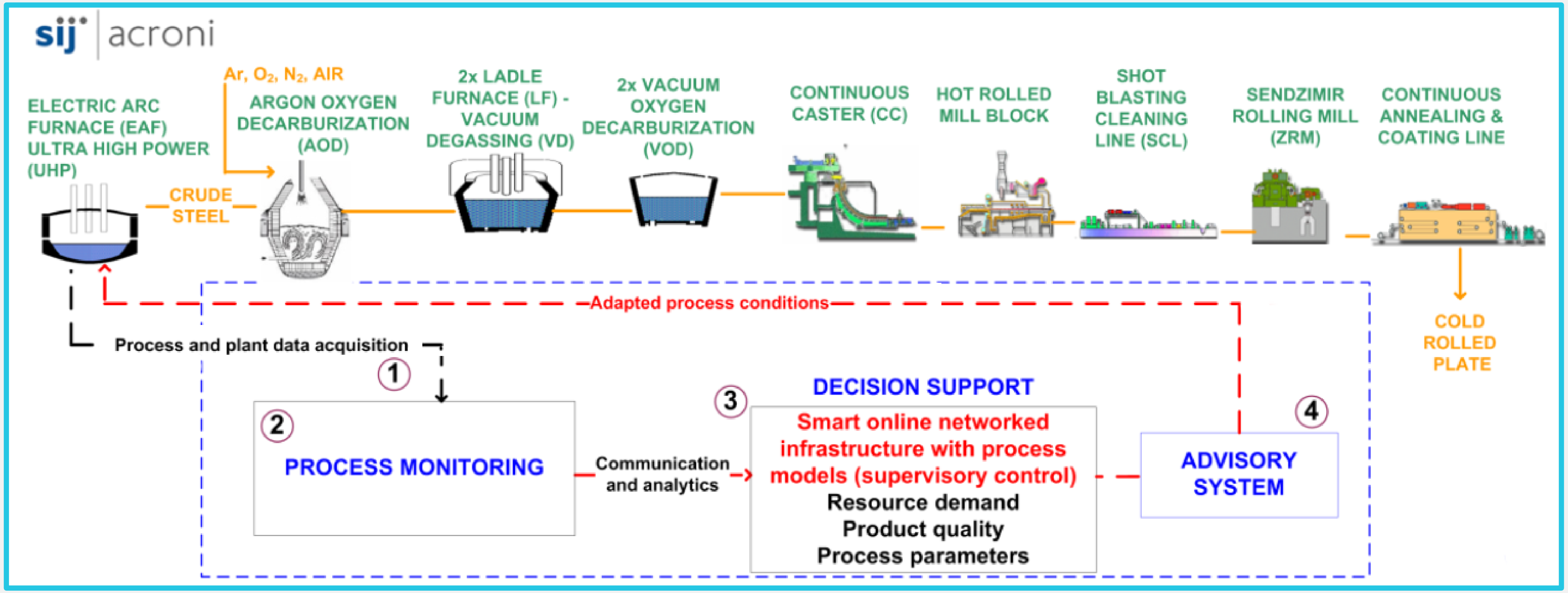
Brief overview

EAF digitalization Use Case

UC1: SIJ Acroni, Faculty of electrical engineering (University of Ljubljana), Siemens

Development of advanced digital solutions for EAF operation support:

- solutions: a combination of online and offline operation support tools,
- goals: operator support, improved KPIs.

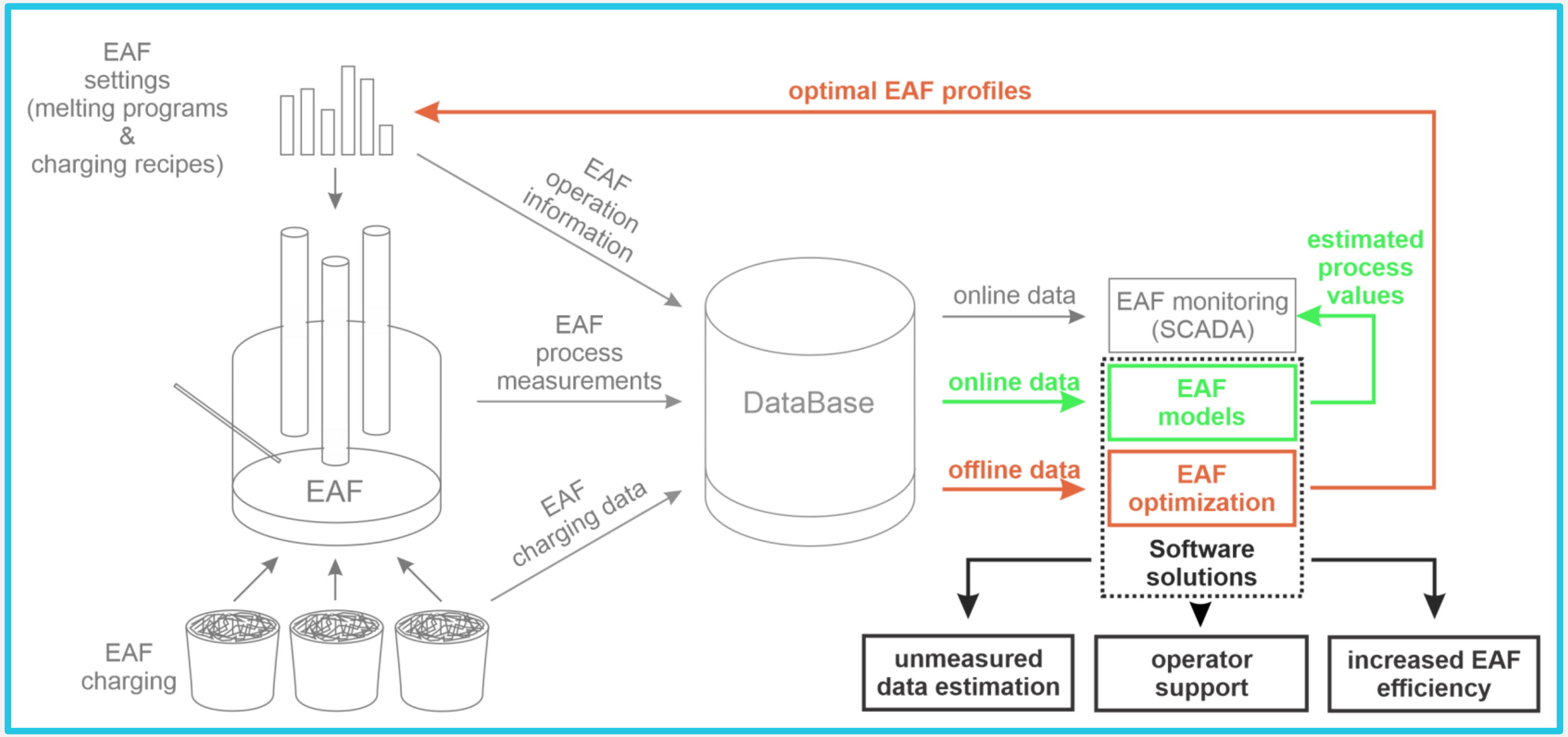


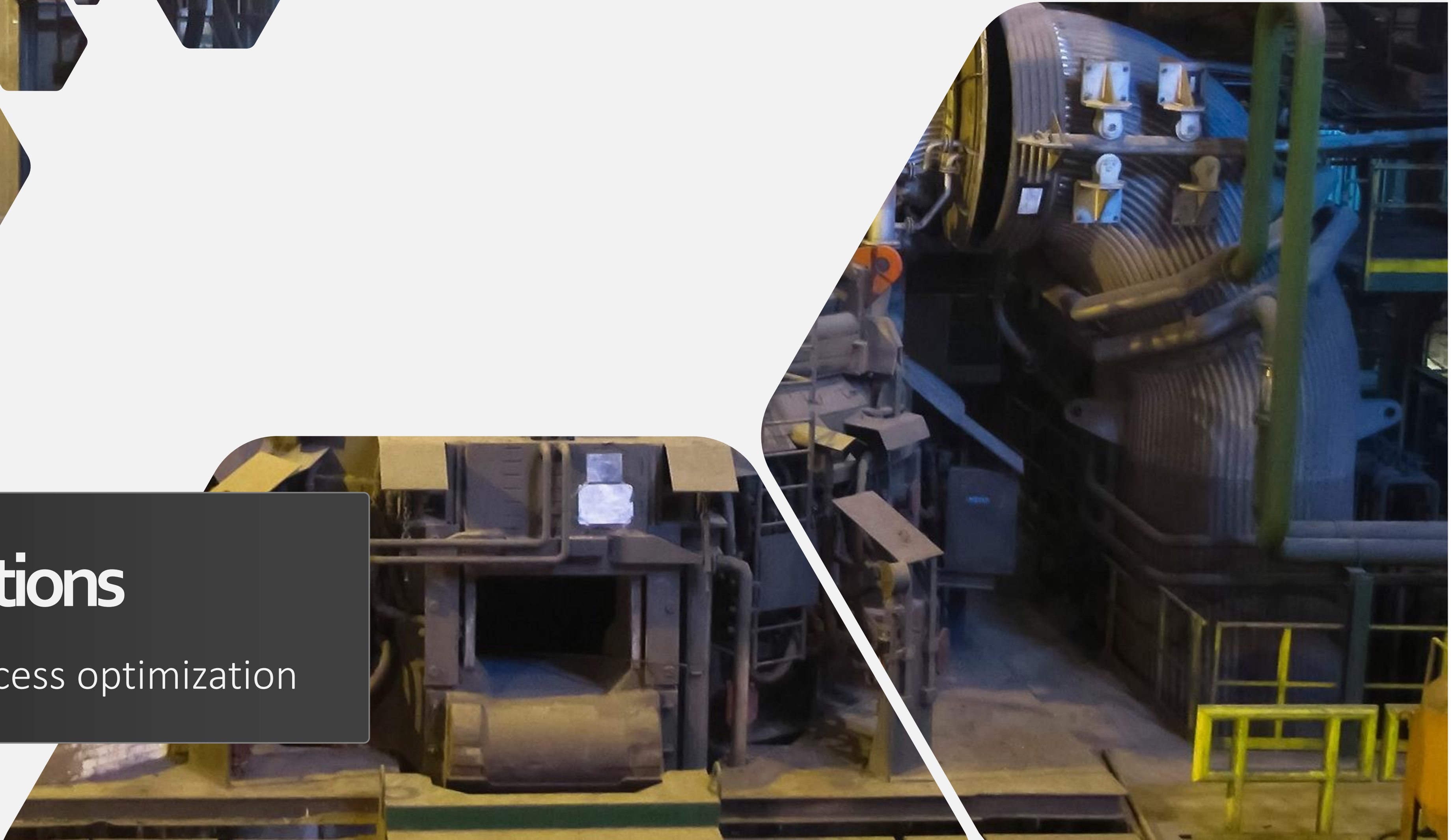
EAF digitalization Use Case

UC1: SIJ Acroni, Faculty of electrical engineering (University of Ljubljana), Siemens

Planned digital solutions for EAF operation support:

1. **mathematical models** for **online**, **parallel simulation** of the EAF process
2. **mathematical models** for **offline simulation** of the EAF process
3. **data-driven models** for **online**, **parallel simulation** of the EAF process
4. **data-driven optimization framework** for **offline** improvement of the melting profiles





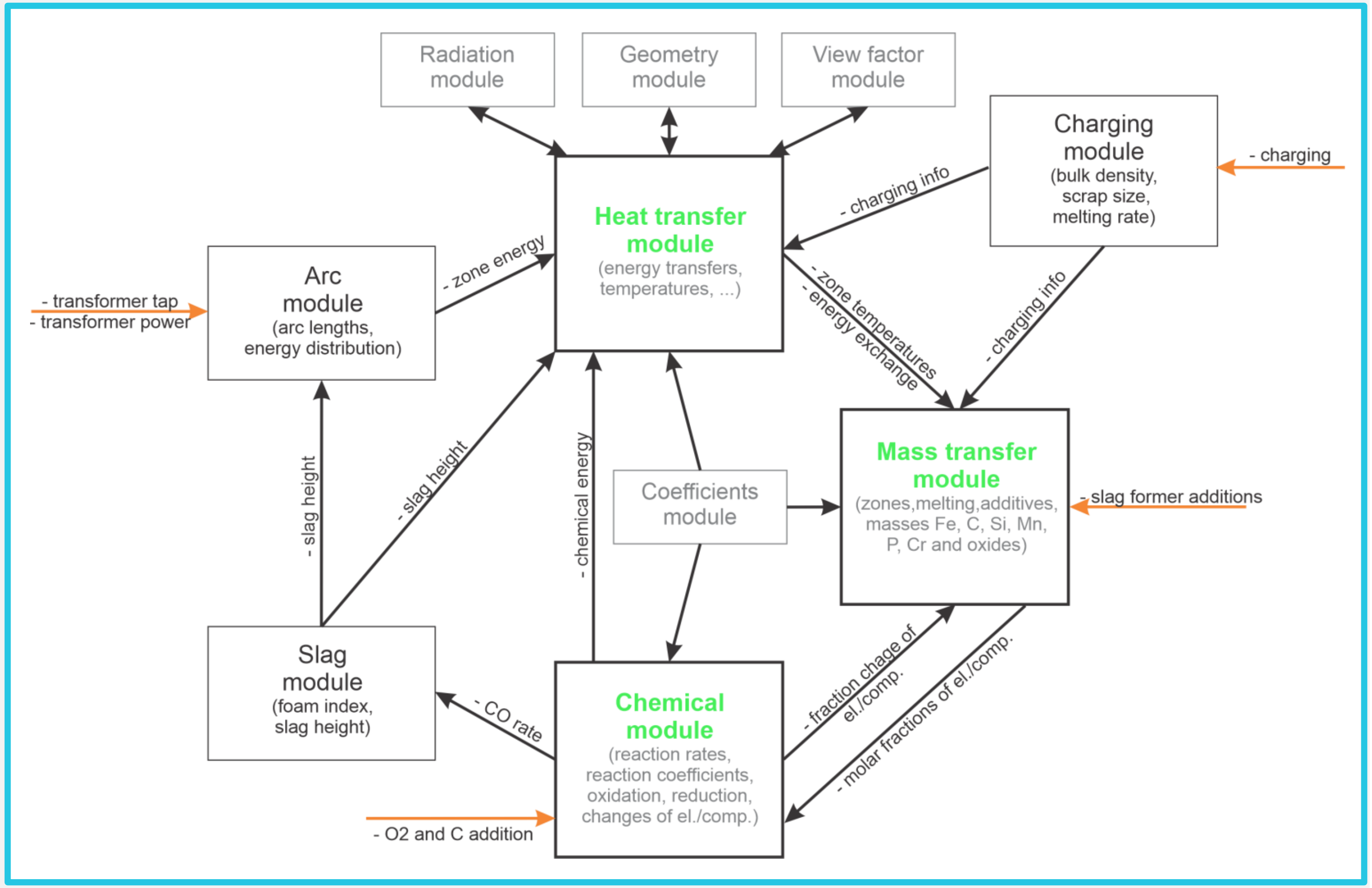
Digital EAF solutions

Process models and process optimization

Digital EAF solutions

Mathematical models

- developed since 2010
- three main model upgrades:
  - V1: 2010-2012
  - V2: 2015-2017
  - V3: 2019-
- latest model developed for **INEVITABLE** in two versions:
  1. **complete structure**, functionality, and calculations
  2. **simplified structure**, limited functionality, and calculations

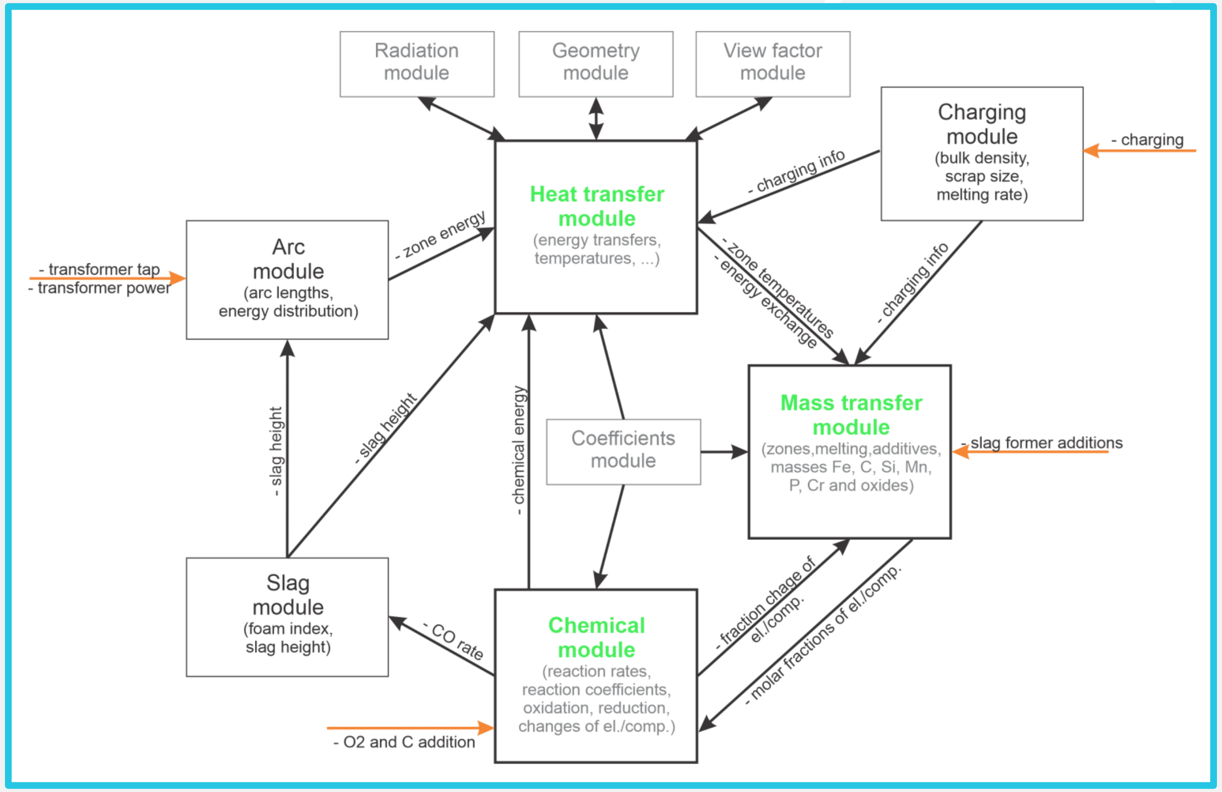


Digital EAF solutions

Mathematical models

Differences between V1 and V3

- overall structure of the model
  - modular design
- additional calculation zones
  - 4 additional zones (solid scrap below/above the bath, electrodes, refractories, cooling water)
- more precise definition of the EAF configuration
  - dimensions, material properties
- simplified EAF geometry
  - cylinders, discs, circles etc.
- simplified melting geometry
  - cylinder-shape melting dynamics
  - solid scrap below and above the bath

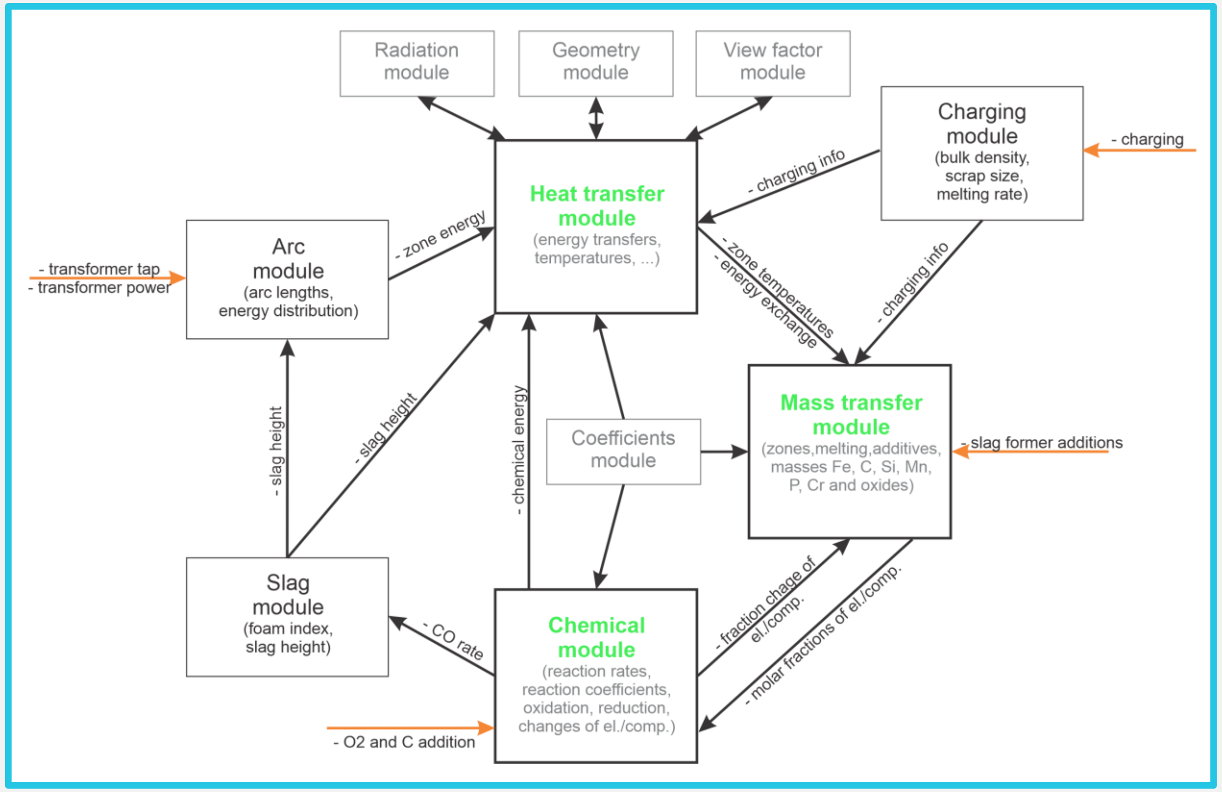


- added arc module
  - calculation of the arc lengths and energy distribution
- modified radiation module
  - new definition of view factors (simplified), according to modified melting geometry

Digital EAF solutions

Mathematical models

- modified chemical module and unification of the related ODEs
- modified energy calculation module
  - modified calculations of heat transfers
  - addition zones for cooling (water in panels/roof)
- modified slag module
  - new calculations for slag foaming, height and influence on energy flows
- added electrode module
- modified calculation of several parameters
  - dependence on current EAF conditions (specific heat capacities, heat transfer coefficients, reaction rates etc.)
- added variable limitations



Digital EAF solutions

Mathematical models

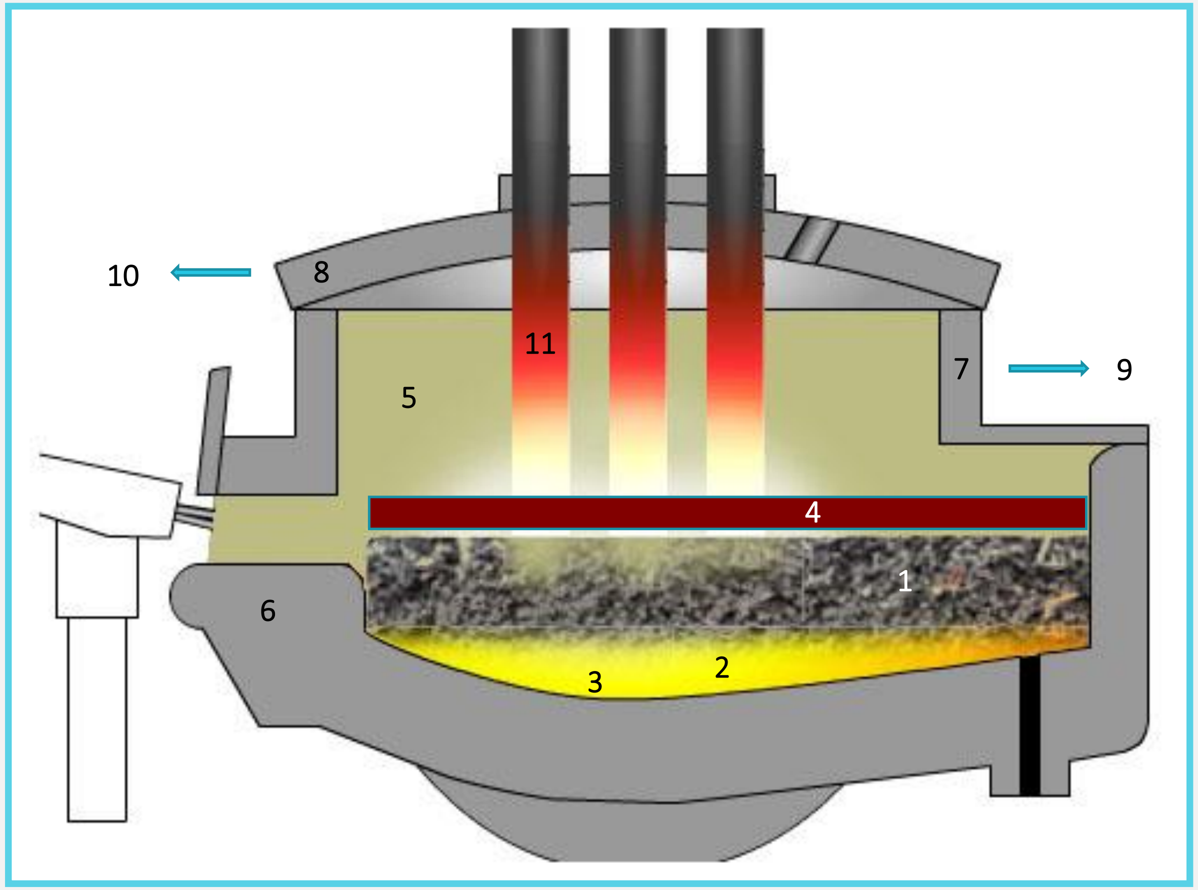
1. **complete structure and calculations (for offline simulation studies):**
    - influence of charging (scrap composition/weight),
    - influence of selected melting programs (recipes) on EAF‘s KPIs:
        - input profile selection,
        - charging times,
        - slag formers addition.
2. **simplified structure and calculations (for online/parallel simulation):**
    - estimation of the bath temperature,
    - estimation of scrap meltdown stage.

Digital EAF solutions

Mathematical models

Generalized zone model:

- each zone possesses equal physical characteristics and parameters,
- division of the EAF to zones:
  1. solid scrap above the bath,
  2. solid scrap submerged in bath,
  3. bath,
  4. slag,
  5. gas,
  6. refractory,
  7. water-cooled panels,
  8. roof,
  9. cooling-water panels,
  10. cooling-water roof,
  11. electrodes.



Digital EAF solutions

Mathematical models

Considering all necessary processes:

- **mass-transfer** (changes in physical states, chemical reactions),
- **heat-transfer** (added electrical energy, chemical energy, losses, entalphies, etc.),
- **chemical** (all important chemical reactions).

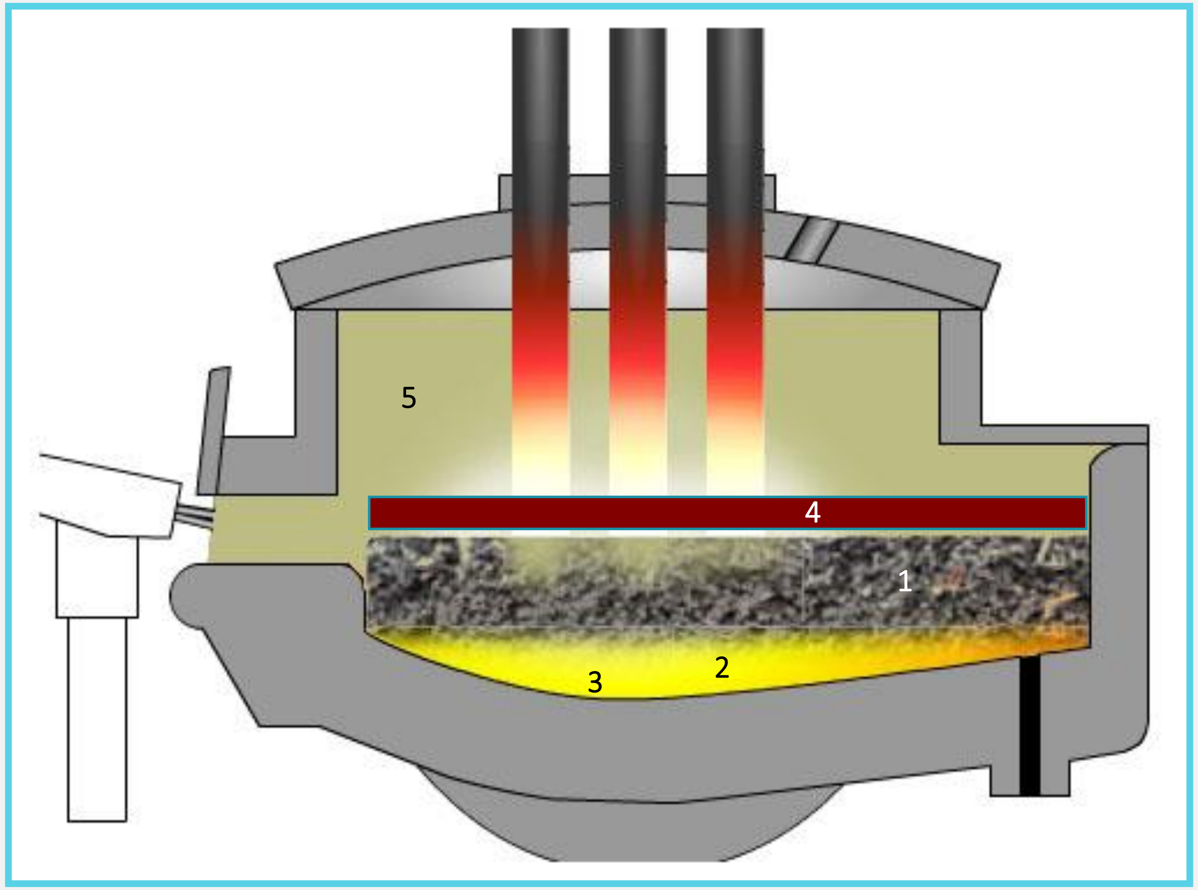
Mathematical equations derived from fundamental physical laws and conclusions of different studies.

Digital EAF solutions

Mathematical models

Mass-transfer module:

- division of the EAF to 5 zones: solid scrap (above/below the bath), bath, slag, gas,
- each zone possesses equal physical characteristics and parameters,
- special attention devoted to properties of the charged scrap (bulk density, melting rate) ,
- elements, considered in calculations:
  - solid scrap and bath: Fe, C, Si, Cr, Mn, P,
  - slag: FeO, SiO_2, MnO, Cr_2O_3, P_2O_5, CaO, MgO,
  - gas zone: N_2, O_2, CO, CO_2,
- 1st order ODEs to obtain mass flows according to the zone temperature and zone energy balance,
- reversible dynamics (cooling / solidification).

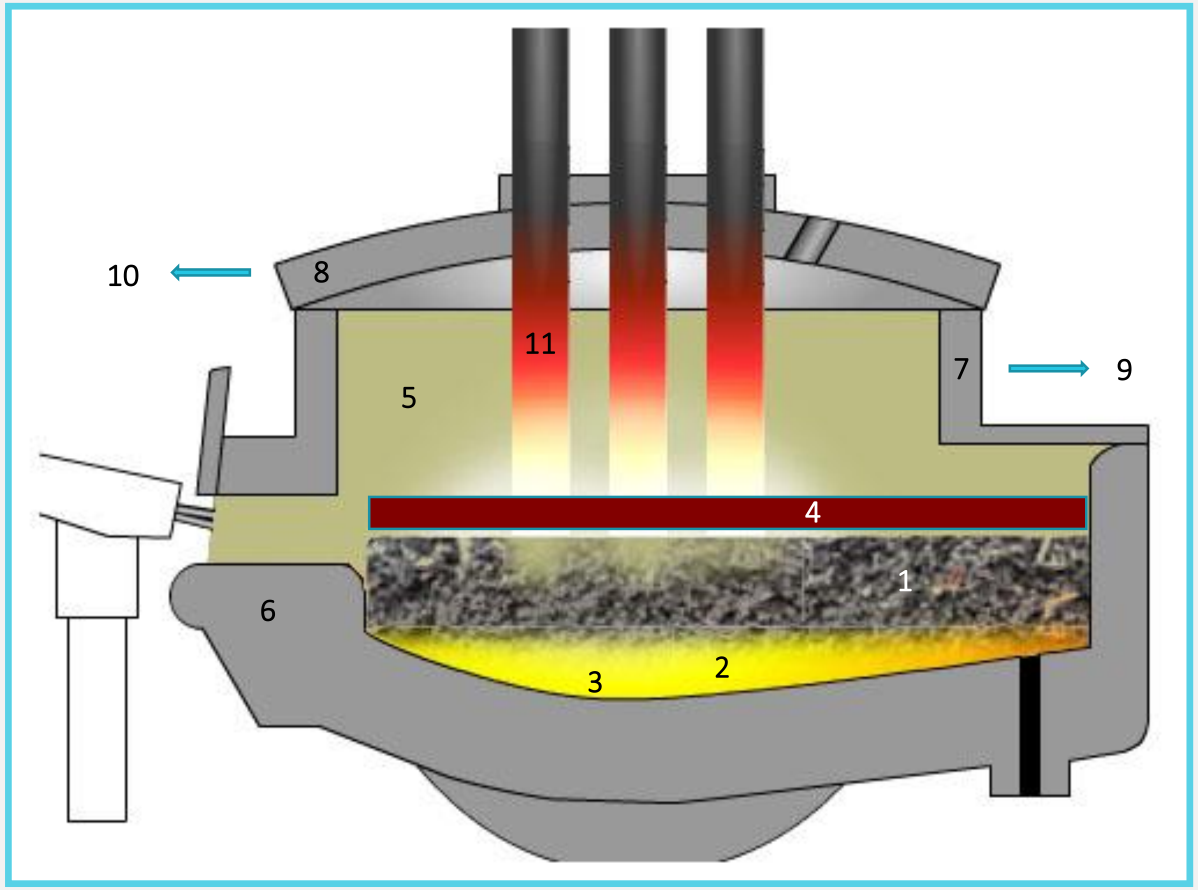


Digital EAF solutions

Mathematical models

Heat-transfer module:

- division of the EAF to 11 zones,
- each zone possesses equal physical characteristics and parameters,
- special attention devoted to scrap melting dynamics (according to charged types/weights),
- 1^{st} order ODEs to obtain zone temperatures according to the zone energy balance,
- radiation module with cylinder-shaped geometry assumed (instead of cone-frustum).



Digital EAF solutions

Mathematical models

Chemical module:

- implementation of all key reactions:
  - oxidation Fe, Si, C, Mn, Cr, P, CO,
  - reduction FeO, SiO_2, MnO, Cr_2O_3, P_2O_5,
- 1^{st} order ODEs to obtain zone reaction rates based on molar equilibrium and composition-dependent reaction rates,
- calculation of the chemical energy,
- slag module for calculation of the slag height according to density, viscosity, surface tension and superficial gas velocity.

Digital EAF solutions

Mathematical models

Parameterization of the crucial parameters using particle swarm optimization (PSO):

- 15 parameters,
- tuning divided into two optimization problems:
    1. refining stage,
    2. melting stage,

$\downarrow$

- less parameters for one optimization problem, i.e., all parameters appear in the melting stage, but not all appear in the refining stage,

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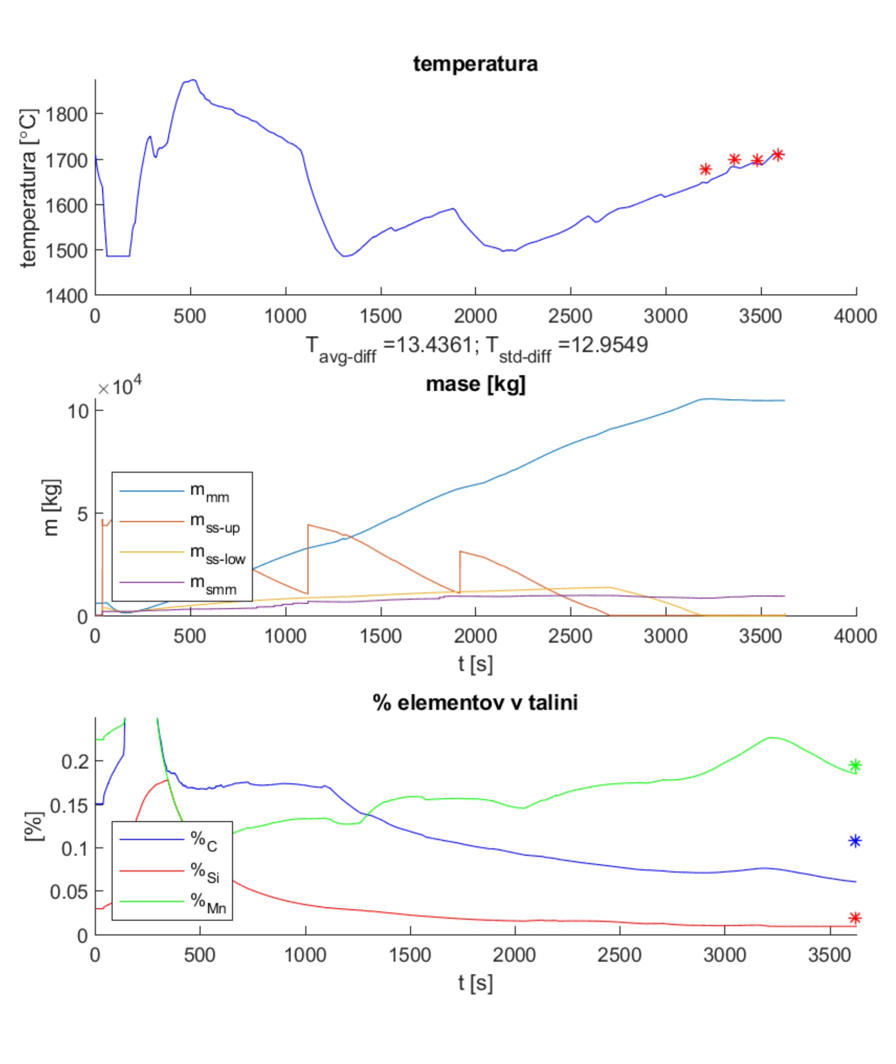
- better parameter estimation, faster convergence.

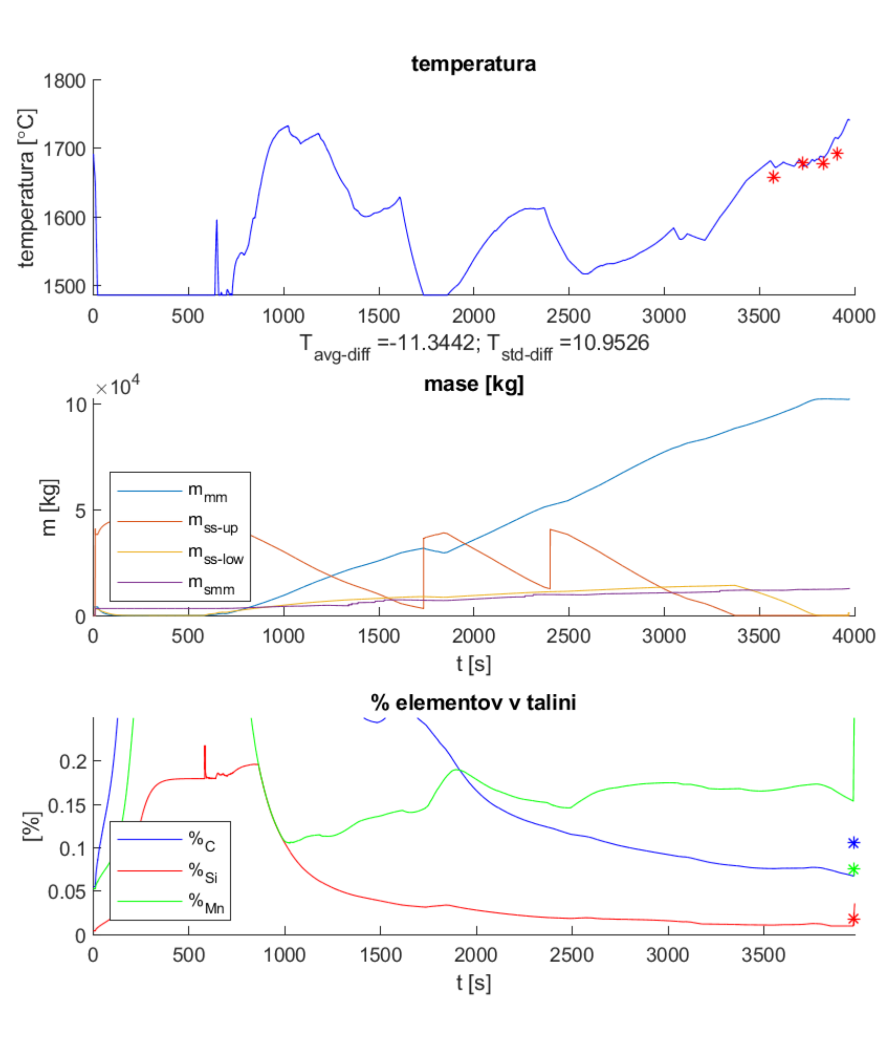
Digital EAF solutions

Mathematical models

Results:

- temperature est.
- stage of melting
- bath composition



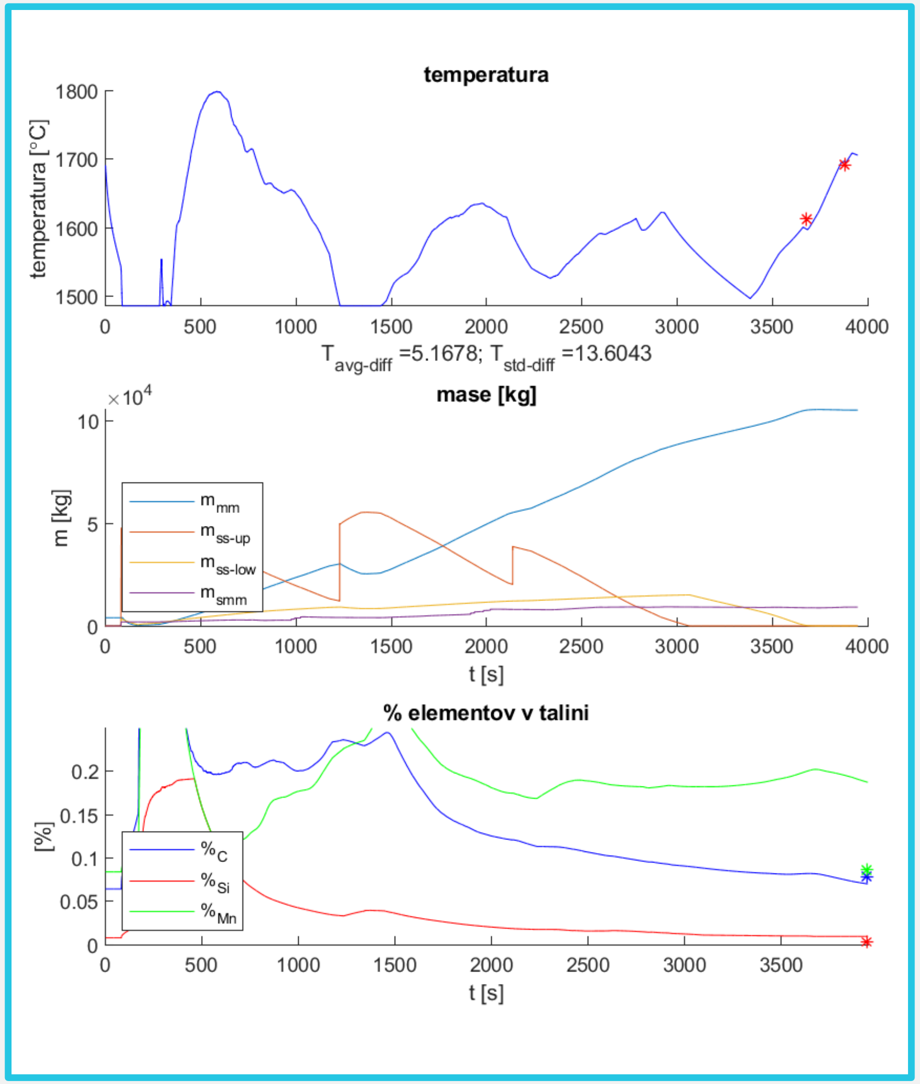


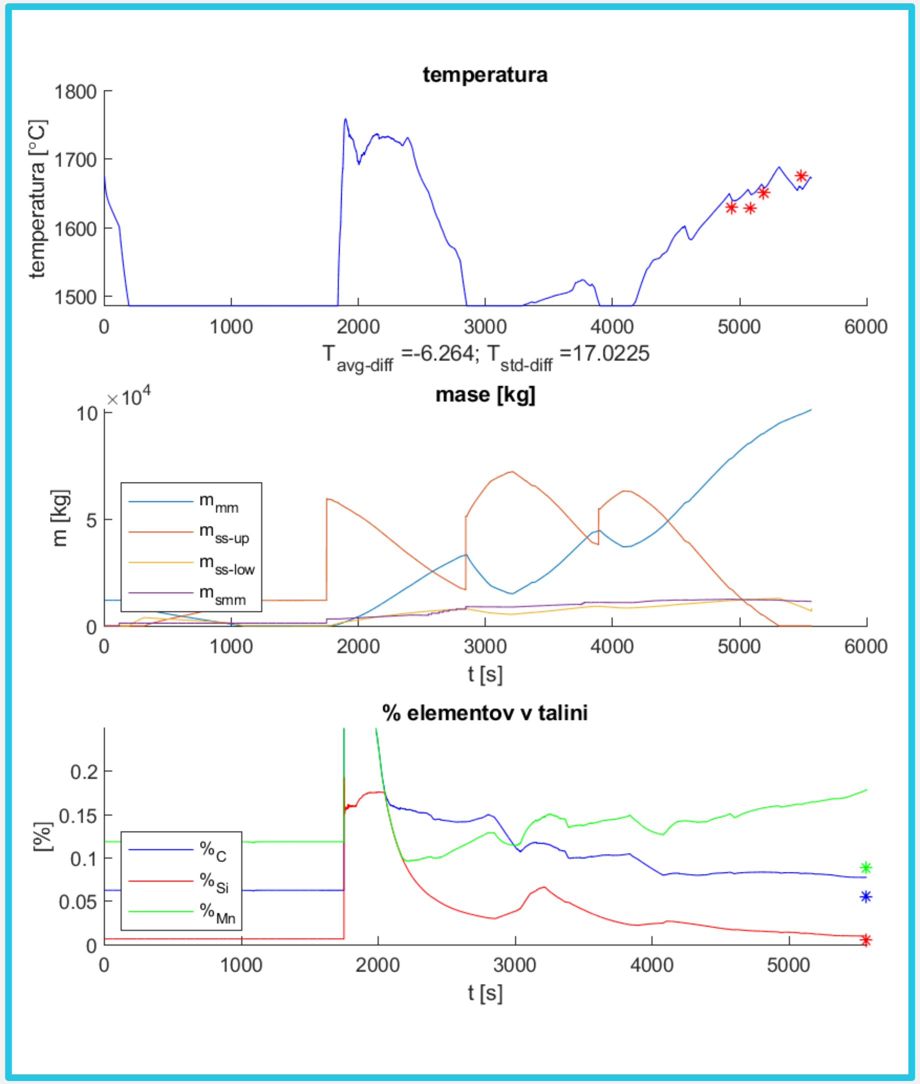
Digital EAF solutions

Mathematical models

Results:

- temperature est.
- stage of melting
- bath composition





Digital EAF solutions

Mathematical models

Conclusion:

- sufficient accuracy of **offline** models, i.e., proper calculations of the necessary values:
    - the influence of **charging**,
    - the influence of **actuation**,
    - total electrical energy consumption for the selected charging and melting program,
    - approximate endpoint bath composition,
- sufficient accuracy of **online** models, i.e., proper calculations of the necessary values:
    - stage of melting,
    - bath temperature estimation (~ 13 ^{o}C MAE, ~ 17 ^{o}C SDE) – not completely parameterized.

Digital EAF solutions

Data-driven models

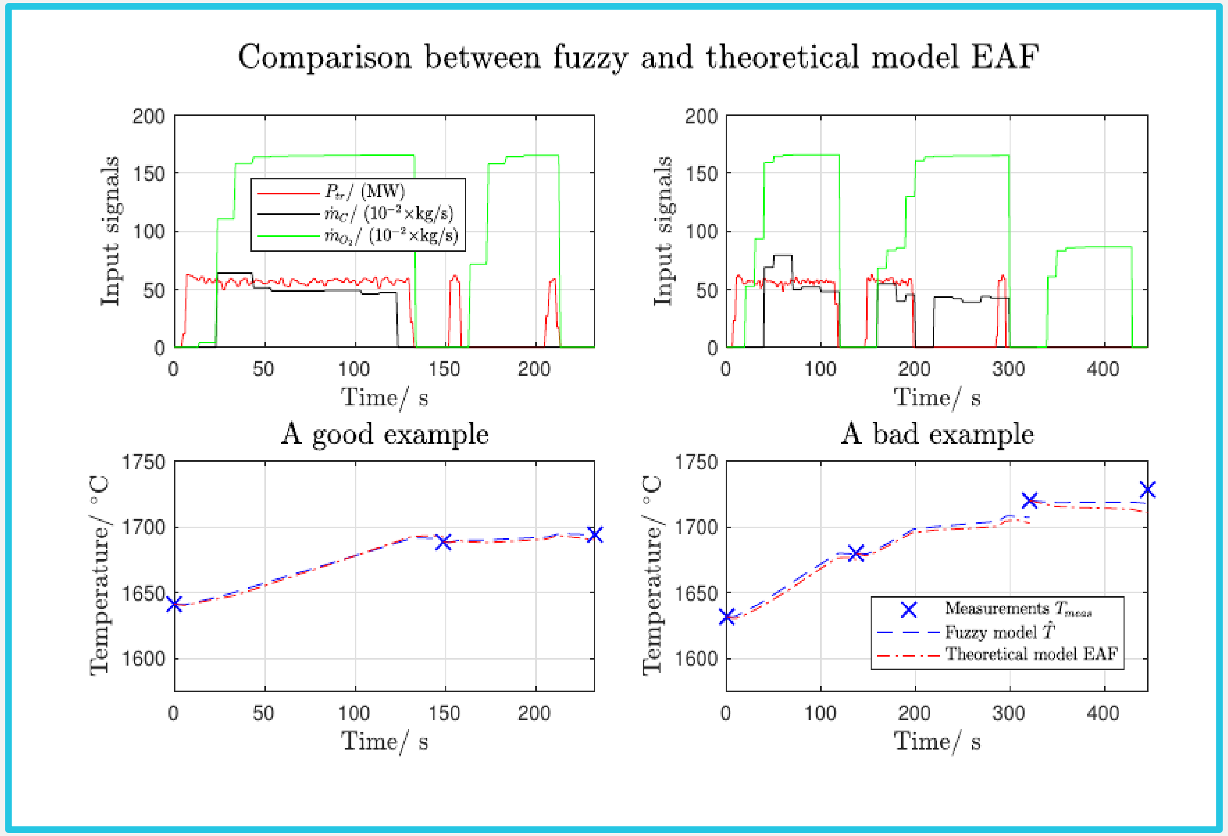
- developed since 2020,
- Takagi-Sugeno fuzzy models for estimation of:
  - bath temperature,
  - dissolved oxygen in the bath,
- due to simplified model structure and insufficient process measurements, the estimation is limited only to the **refining stage**,
- inputs:
  - charged scrap mass,
  - input profiles of: transformer power, oxygen lancing, carbon injection,
- first temperature or oxygen measurement is used as an **initial condition**,
- two estimation options:
  - „one“ step: reinitialization of the model with each measurement,
  - „multi“ step: no intermediate reinitializations.

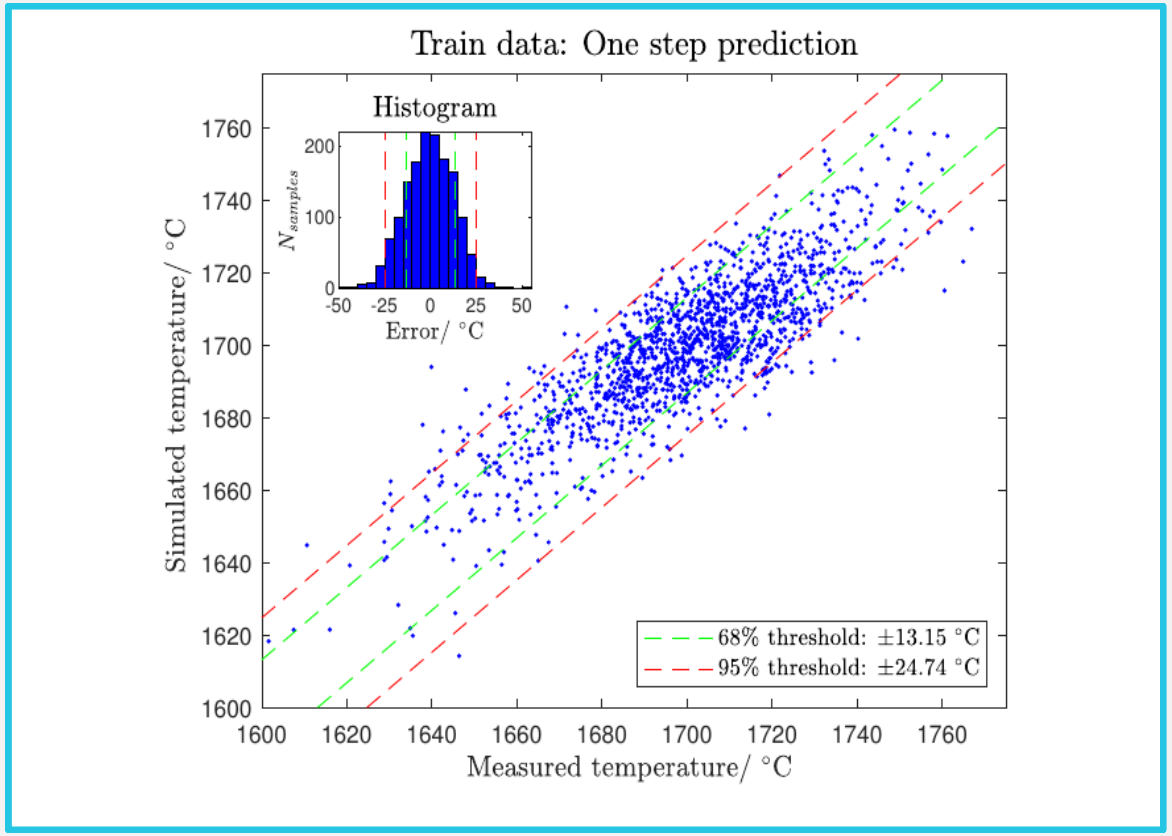
Digital EAF solutions

Data-driven models

Results:

- temperature estimation
- estimation accuracy: 10 ^{o}C MAE, 13 ^{o}C SDE



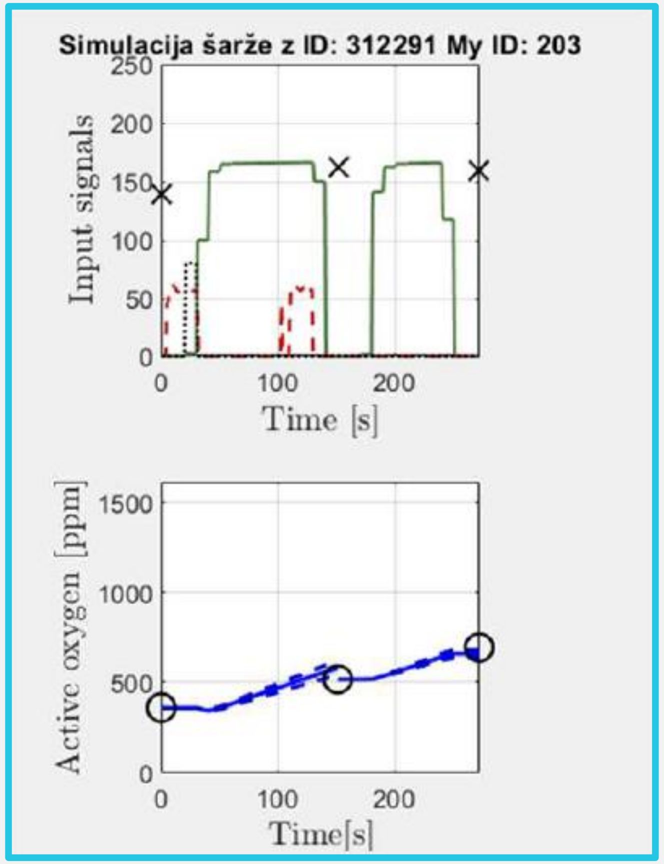


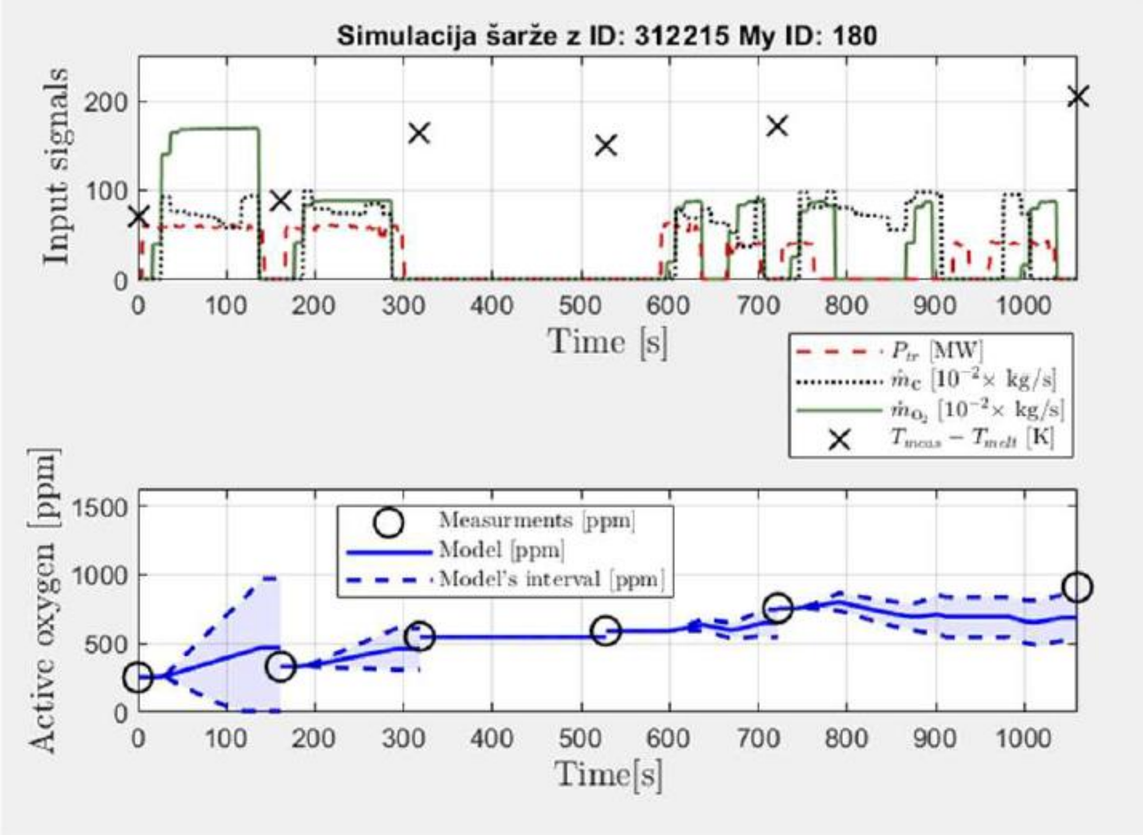
Digital EAF solutions

Data-driven models

Results:

- dissolved oxygen amount estimation
- estimation accuracy: 120 ppm MAE, 160 ppm SDE





Digital EAF solutions

Data-driven models

Conclusion:

- better accuracy than theoretical EAF model, when estimating the bath temperature,
- theoretical model does not calculate O_2 ppm,
- integration of the data-driven models into the final solution,
- **challenges:**
  - incorrect initial measurement,
  - incompletely melted scrap,
  - inhomogenous bath (much better results, if the bath is stirred).

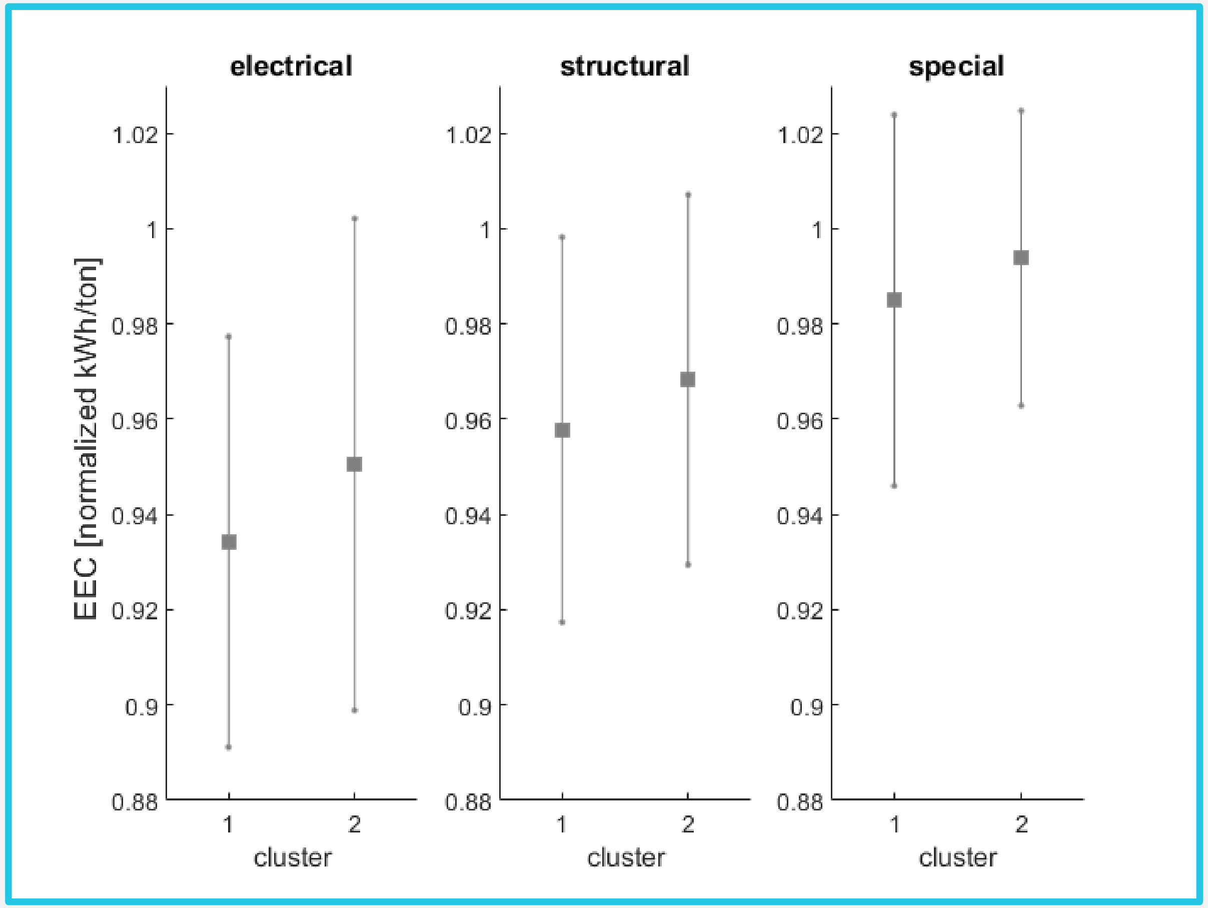
	Acroni's EAF	similar EAF with stirring
bath temperature	10 ^oC MAE, 13 ^oC SDE	7 ^oC MAE, 10 ^oC SDE
dissolved O_2	120 ppm MAE, 160 ppm SDE	80 ppm MAE, 100 ppm SDE

Digital EAF solutions

EAF optimization framework

Brief overview on the optimization framework:

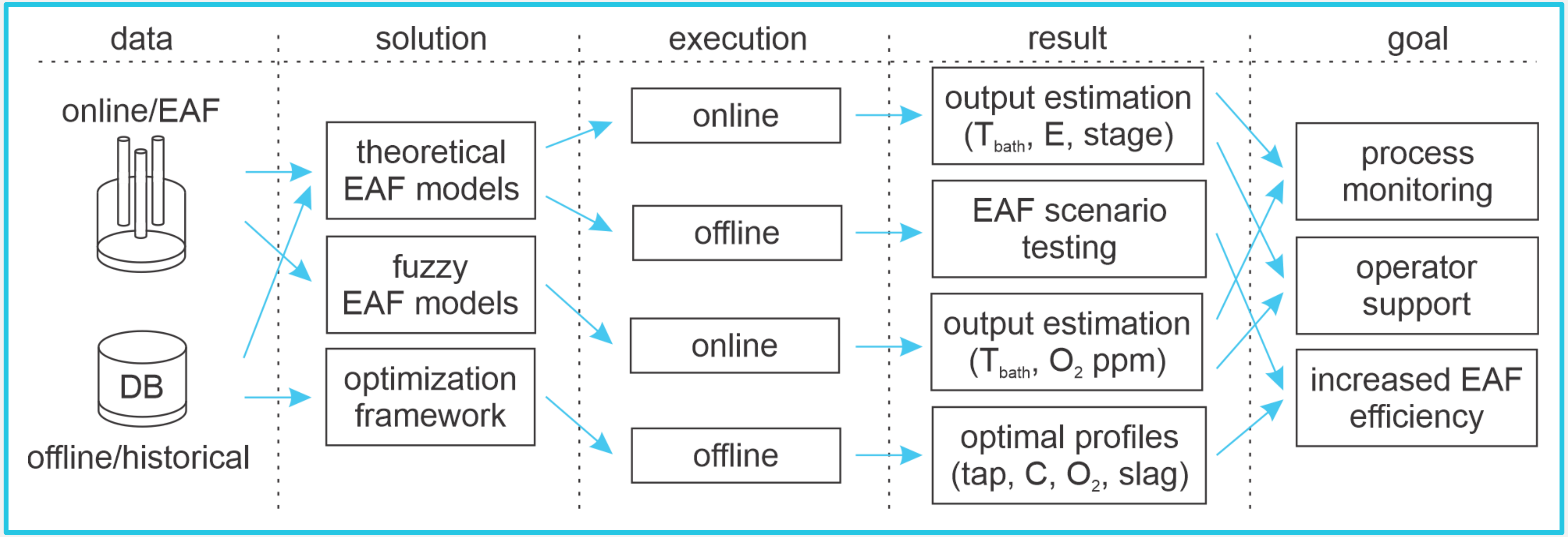
- in development
- using historical data and different data-manipulation methods (clustering, classification, regression, neuro-fuzzy modelling etc.) to find the relations between:
    - charging,
    - input profiles,
- and:
    - electrical energy consumption,
    - tap-to-tap time.



Digital EAF solutions

Overview of all solutions

Envisioned application of the solutions to industrial environment



Digital EAF solutions

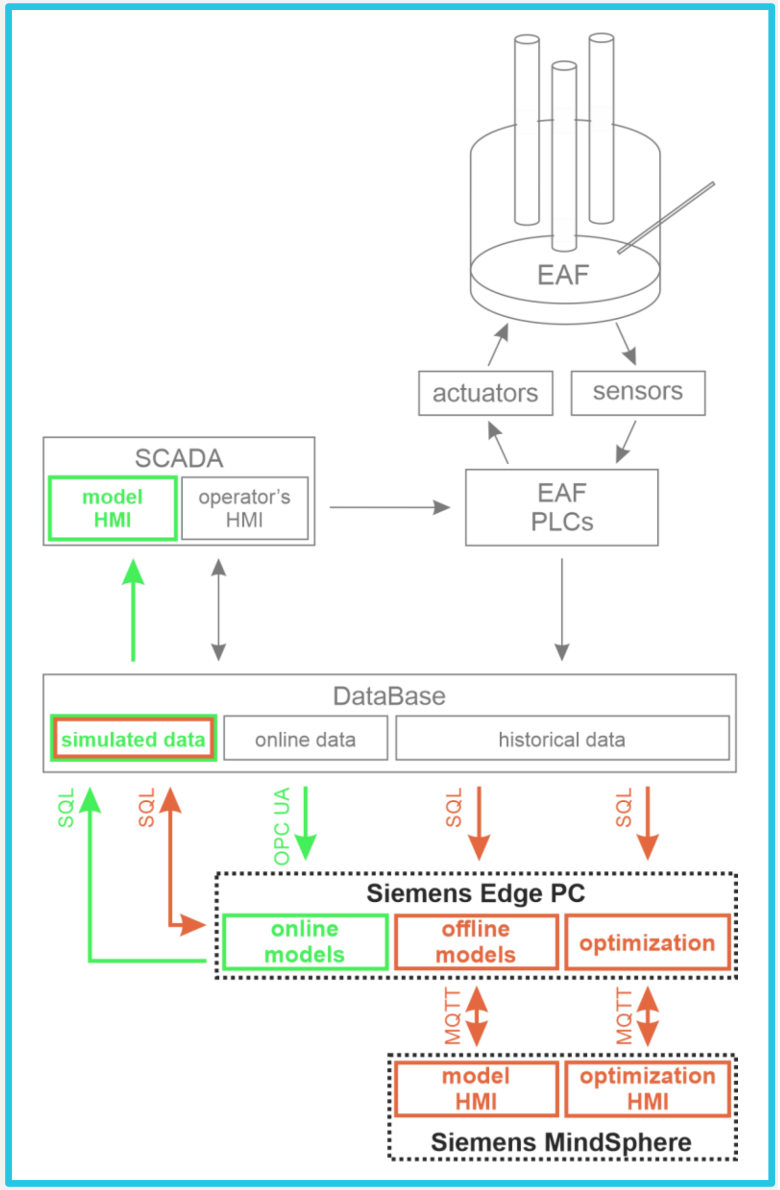
Digitalization infrastructure

Envisioned application of the solutions in terms of established digital infrastructure and environments:

- cloud/edge computing (Siemens Edge, Mindsphere),
- all solution executed on Edge PC,
- existent or new human-machine interfaces:
  - **existent SCADA HMIs** for online process models (bath temperature, dissolved O_2),
  - **new HMIs in Mindsphere** for all offline models and optimization framework,
- additional database tables for obtained results.

MindSphere

Edge Streaming Analytics
Provided by SIEMENS



Conclusion and further work

Planned activities in the scope of the INEVITABLE project

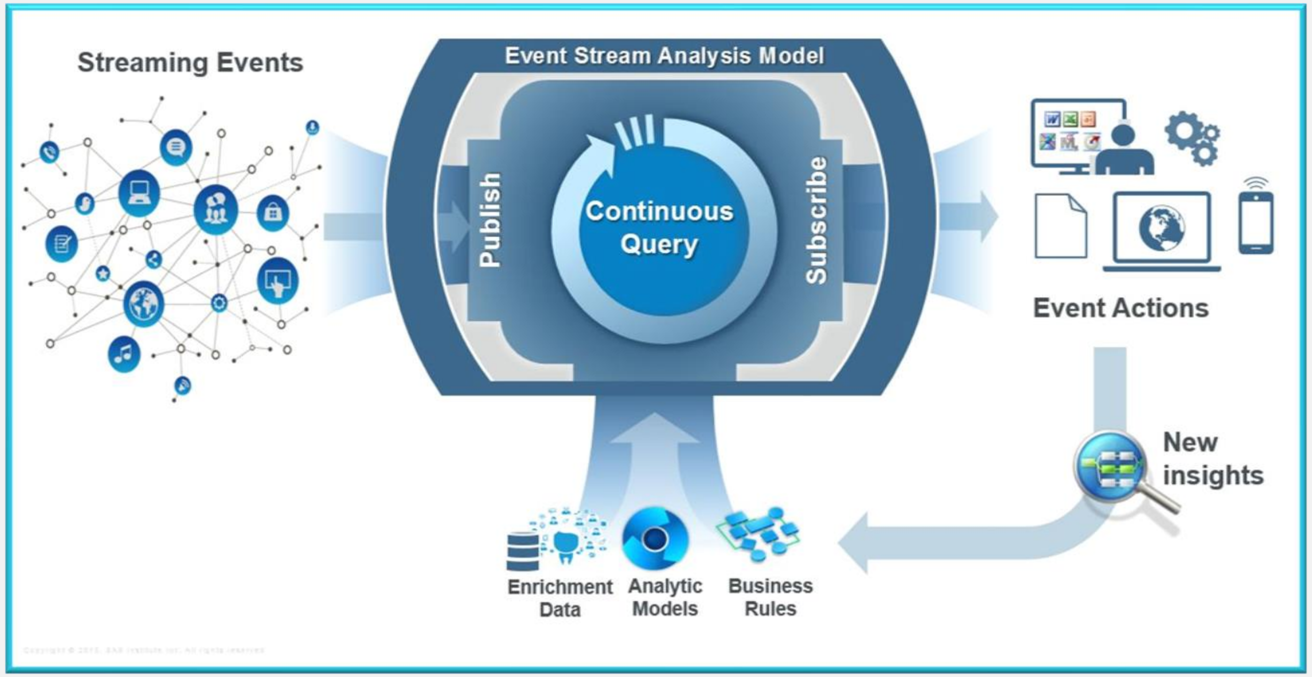
Conclusion and further work

In progress:

- finalization of digital solutions and their preparation for industrial environment in the scope of the ongoing EU project **INEVITABLE**,

Further work:

- recoding of the solutions to **Python**,
- application of the solutions to **Edge device**,
- design and development of **user interfaces**,
- **testing** and **validation** of the installed software,
- assessment of the **KPIs** before and after the digitalization upgrade.



Thank you!

Vito Logar

+386 1 4768 278

vito.logar@fe.uni-lj.si

msc.fe.uni-lj.si

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