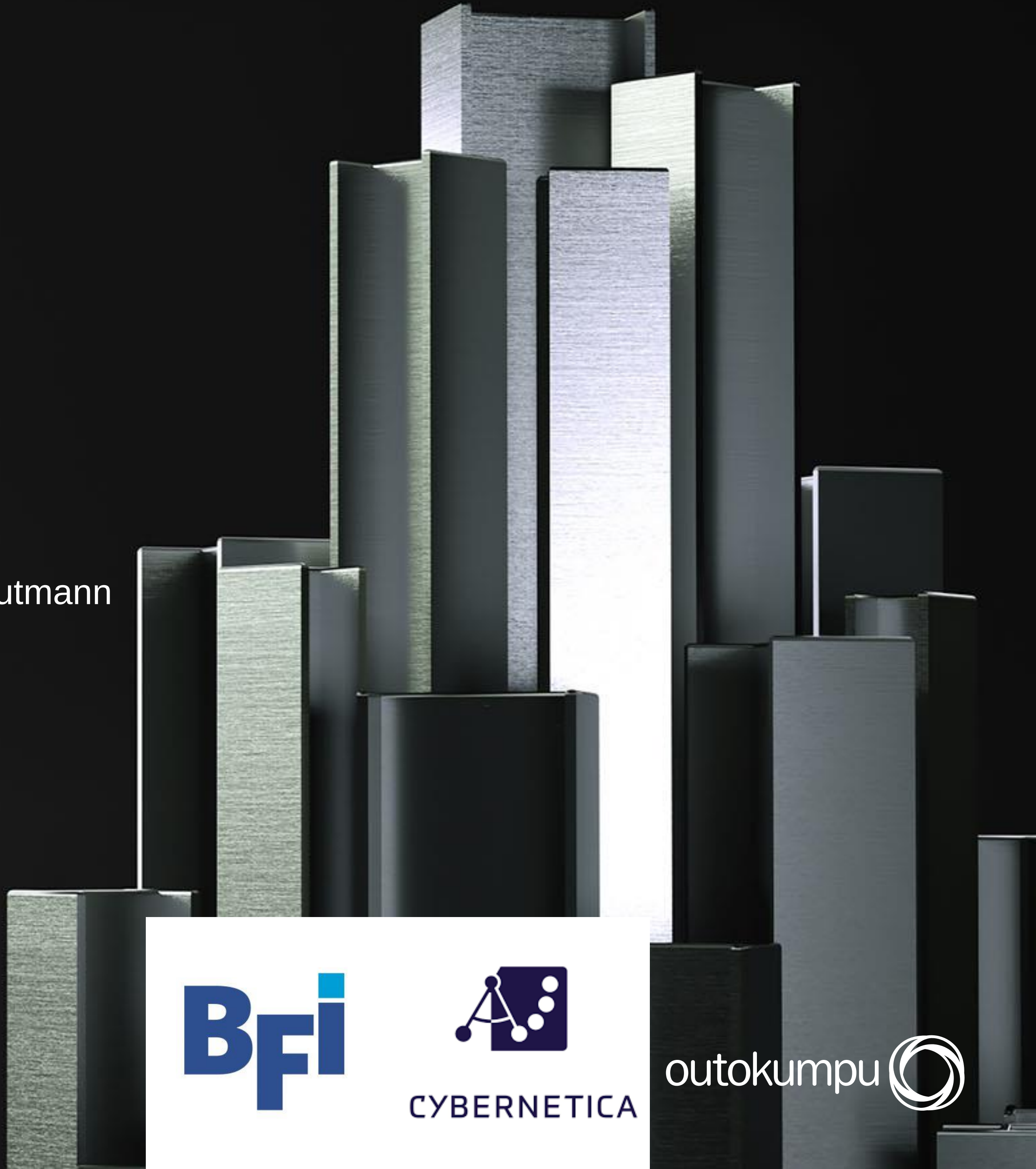
Preliminary experiences from the application of model predictive control for the EAF process in stainless steelmaking

V.-V. Visuri, S. Jawahery, N. Hyttinen, S.O. Wasbø, and M. Schlautmann

4th European Academic Symposium on EAF Steelmaking



June 18, 2021

Ville-Valtteri Visuri, Docent, D.Sc. (Tech.)
R&D Manager – Modeling
Research and Development

BFI

CYBERNETICA

outokumpu

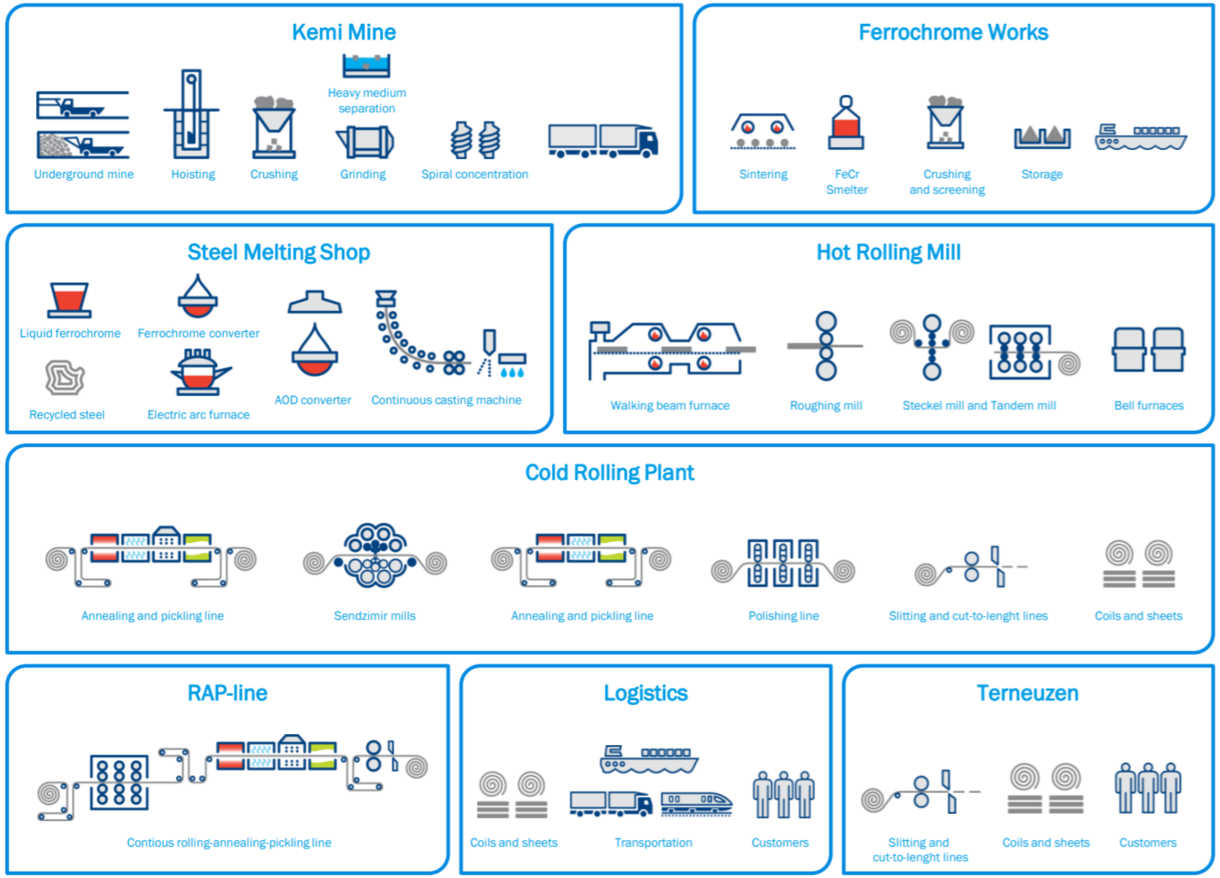
Outline

- Introduction
- Materials and methods
- Results and discussion
- Conclusions and outlook
- Acknowledgements
- Special issue

Introduction

Tornio works

- Tornio works is an integrated steel mill.
  - ferrochrome factory
  - meltshop
  - cold rolling mill
  - continuous rolling-annealing-pickling line.
- The meltshop consists of two production lines with a total annual production capacity of 1.5 million tonnes.
- The lines 1 and 2 operate two AC EAFs with nominal capacities of 85 and 140 tonnes, respectively.



Introduction

Background

- A major challenge for the operation of the EAF process is that the measurements available are either discontinuous or indirect.
- To this end, modelling tools have been developed.
- In recent decades, also fundamental process models have been applied for online control of the EAF process.
- An exhaustive review of the available models was presented recently by Hay et al. [1].

Reference
[1] T. Hay et al, Steel Res. Int., 92(3): 2000395, 2021.

Introduction

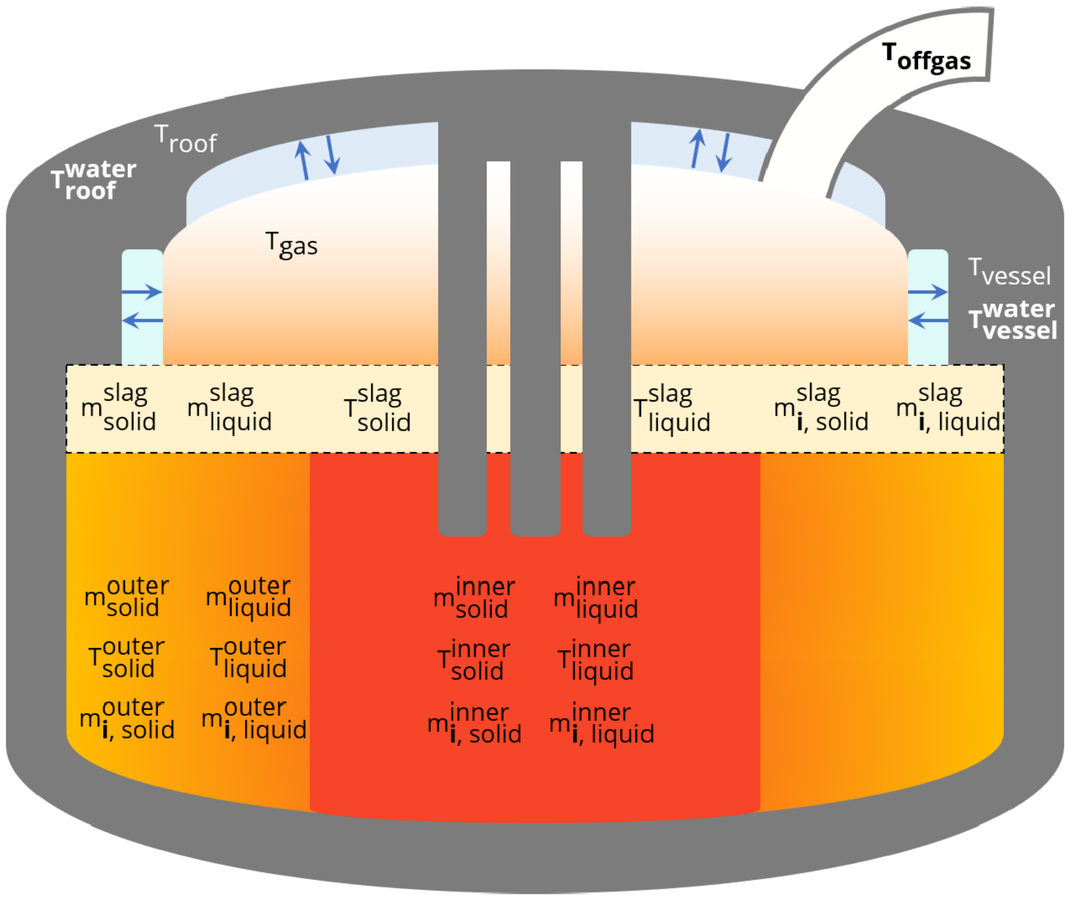
Aims

- In the MORSE project, mathematical models for online monitoring and control of the EAF process have been developed and adapted by BFI and Cybernetica.
- They have been integrated into the Cenit framework of Cybernetica for online application.
- The aim was to use model-based control to minimize batch time and cumulative energy losses per heat.
- The EAF model was tested at line 2, which operates a 140-tonne AC EAF.
  - 160 MVA transformer power
  - Natural gas burners.

Materials and methods

Overall

- The model accounts for the following state variables:
  - Total mass and temperature of the
    metal (liquid and solid)
    slag (liquid and solid)
  - Mass of components in the
    metal (liquid and solid)
    slag (liquid and solid)
  - Temperature of the
    gas (freeboard and offgas)
    cooling water (wall and roof)
    vessel (wall and roof)



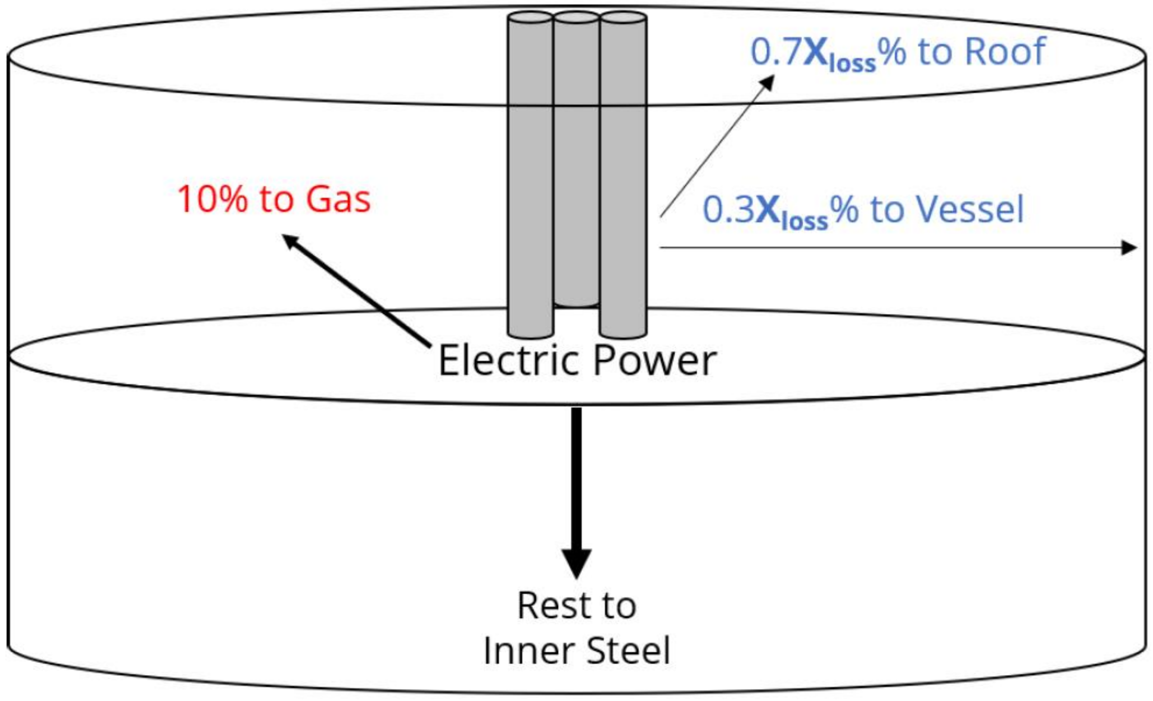
Schematic illustration of the state variables.

outokumpu

Materials and methods

Heat balance

- Energy is supplied by electrical power, gas burners and chemical reactions.
- The fractions of the energy division are treated as constant parameters.
- The electric energy is divided between gas phase, furnace (walls and roof) and metal (solid and liquid).
- The energy from the burners is divided between the gas phase and metal (solid and liquid). No heat exchange with the furnace is assumed.



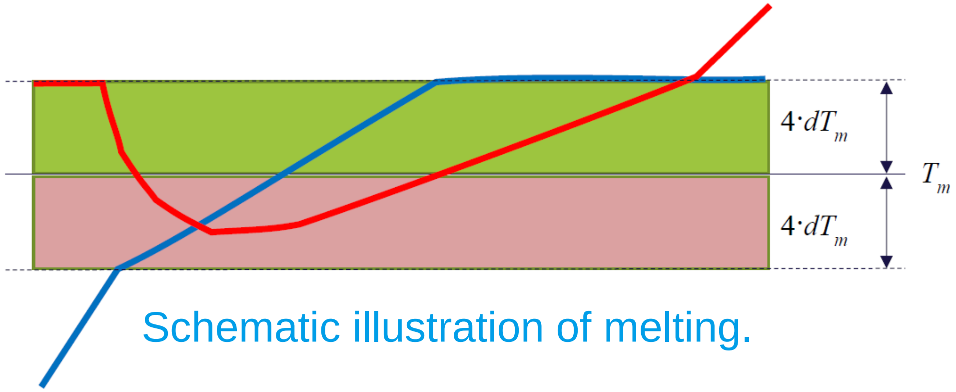
Materials and methods

Melting and freezing

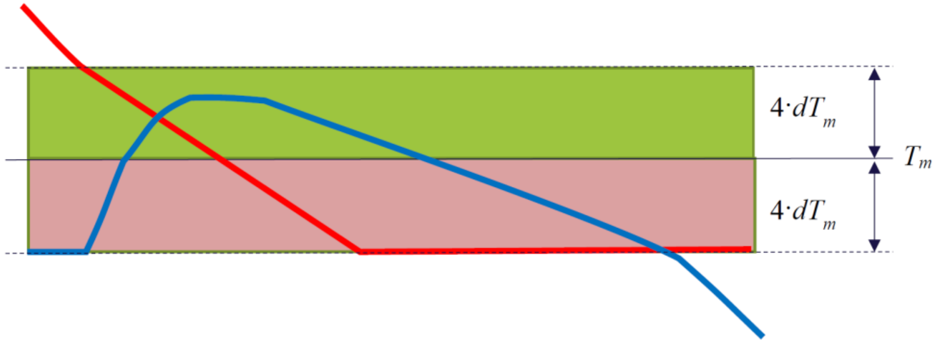
- Melting takes place when the solid temperature (blue line) increases above the lower boundary for the phase change region.
  - The liquid temperature (red line) then changes from its virtual value and eventually the solid mass disappears.
- Freezing takes place when the liquid temperature (red line) decreases below the upper boundary of the phase change region.
- The melting and freezing rates are given by

$$r_{\mathrm{melt}} = k_{\mathrm{melt}} m_{\mathrm{solid}} \frac{\max(0, (T_{\mathrm{solid}} + \mathrm{d}T_{\mathrm{m}}) - T_{\mathrm{m}})}{2\mathrm{d}T_{\mathrm{m}}}$$

$$r_{\mathrm{freeze}} = k_{\mathrm{freeze}} m_{\mathrm{liquid}} \frac{\max\left(0, T_{\mathrm{m}} - \left(T_{\mathrm{liquid}} - \mathrm{d}T_{\mathrm{m}}\right)\right)}{2\mathrm{d}T_{\mathrm{m}}}$$



Schematic illustration of melting.



Schematic illustration of freezing.

Materials and methods

Chemical reactions

- The model accounts for combustion of natural gas and CO as well as the oxidation of Fe, C, Si and Cr by oxygen.
- The model accounts also for reversible equilibrium reactions between metal and slag.

Components and reactions.

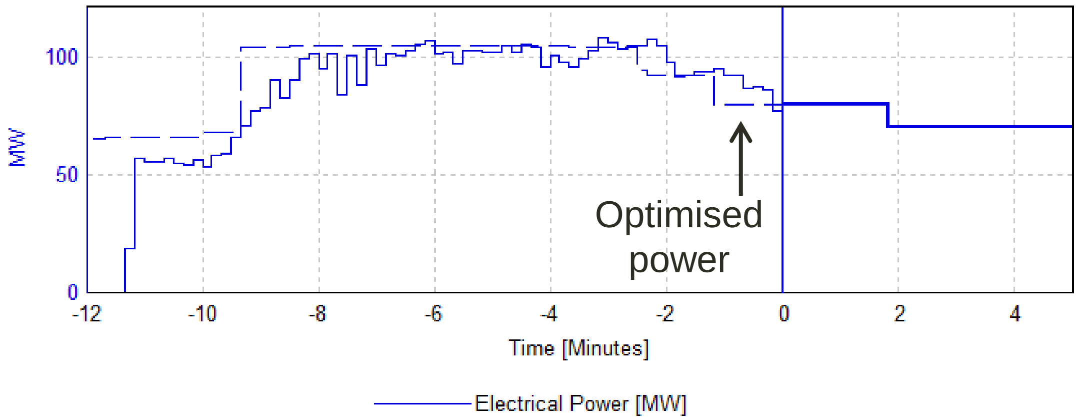
Components	Phase(s)	Reactive with oxygen	Equilibrium reaction
Fe	Liquid, solid	X	X
C	Liquid, solid	X	X
Cr	Liquid, solid	X	X
Si	Liquid, solid	X	X
Mn	Liquid, solid	–	X
FeO	Slag	–	X
SiO_2	Slag	–	X
Cr_2O_3	Slag	–	X
MnO	Slag	–	X

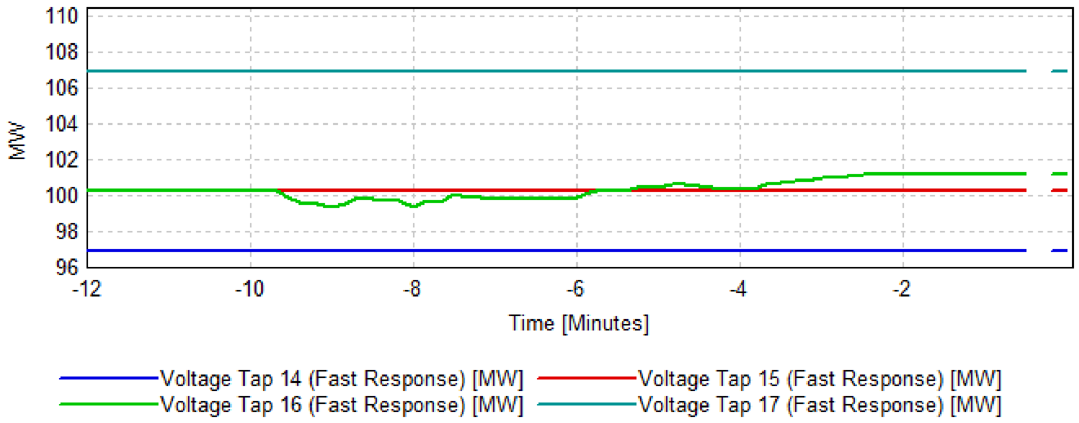
outokumpu

Materials and methods

MPC functionality

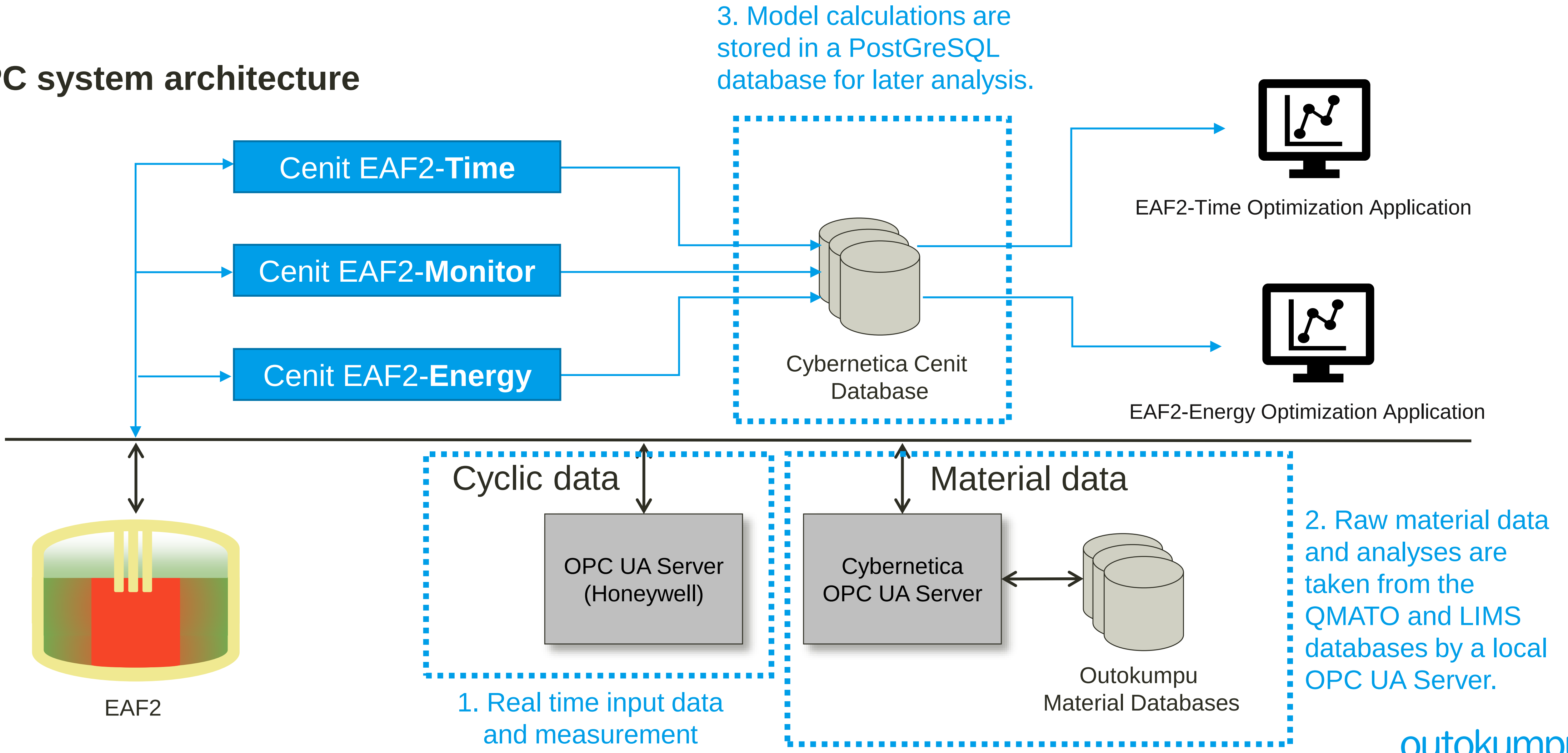
- The non-linear MPC (NMPC) applications continuously produce optimized electric power profiles.
- The allowed power outputs are constrained to not deviate beyond a given interval from a pre-defined recipe profile.
- The optimized electric power is then converted to a voltage tap recommendation for the operators.
  - ❑ A setpoint deadband solution is employed to avoid oscillations or sudden changes in the voltage taps.
  - ❑ Future optimized voltage taps are not restricted by deadband and the deadband is disabled when the power is off.





Materials and methods

MPC system architecture



outokumpu

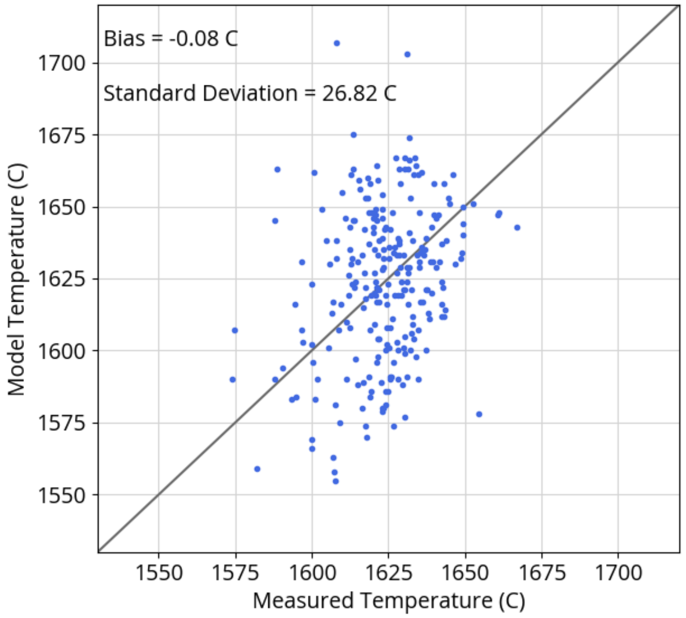
Results and discussion

Offline simulations

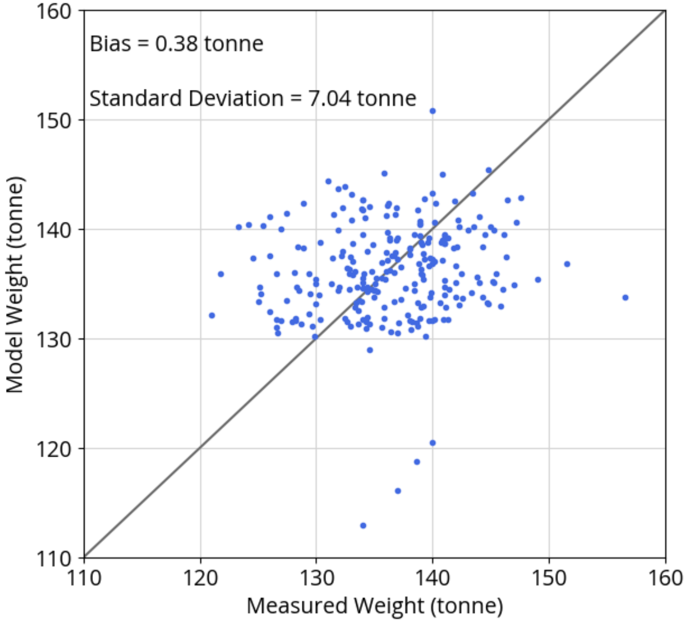
- The offline simulations were conducted for a total of 247 heats.
- Standard deviations:

  Final temperature ~ 27 °C
  Weight of the metal ~ 7 tonnes

- The predictions for are scattered approximately evenly on both sides of the diagonal.



Final temperature of the metal bath



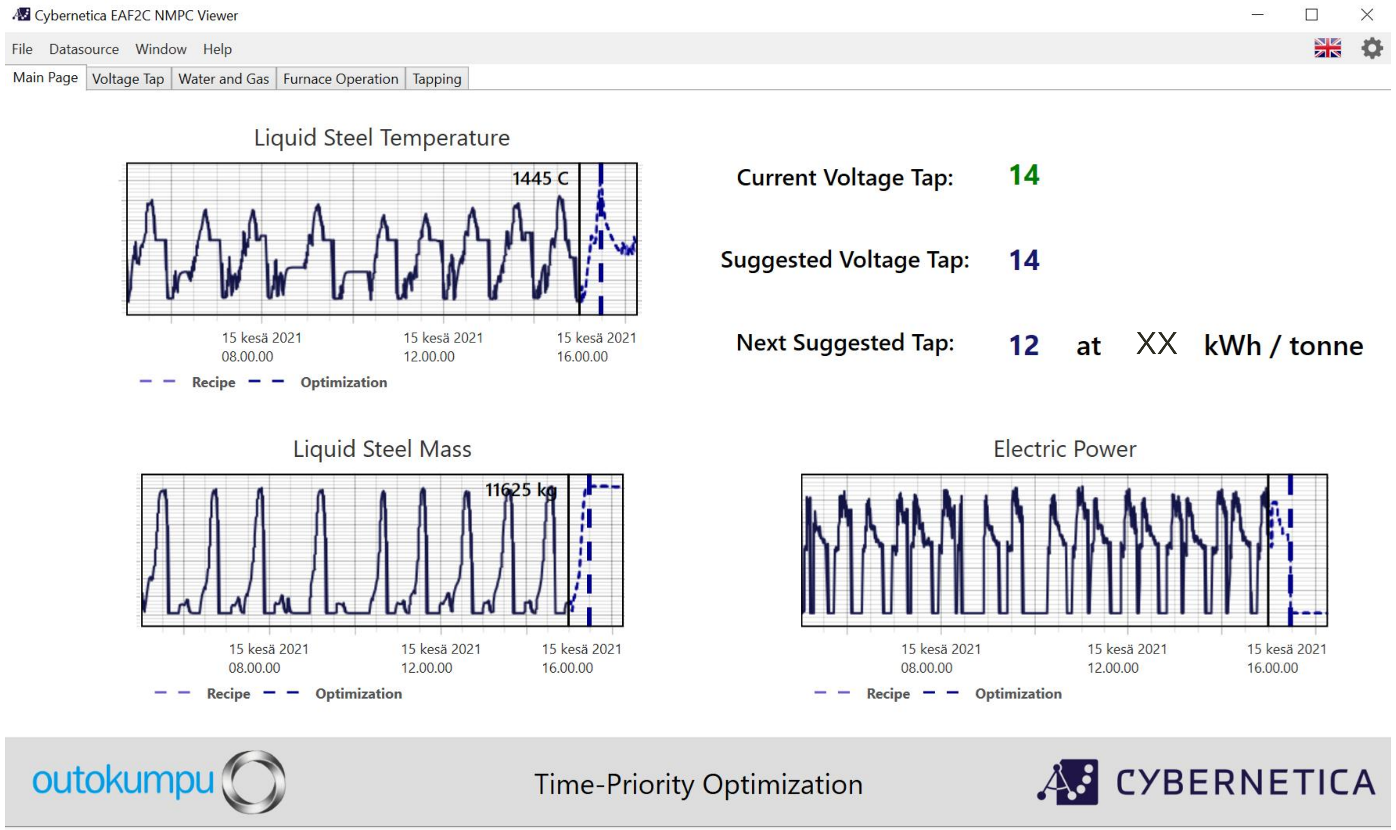
Final weight of the metal bath

outokumpu

Results and discussion

Preliminary testing of the NMPC functionality

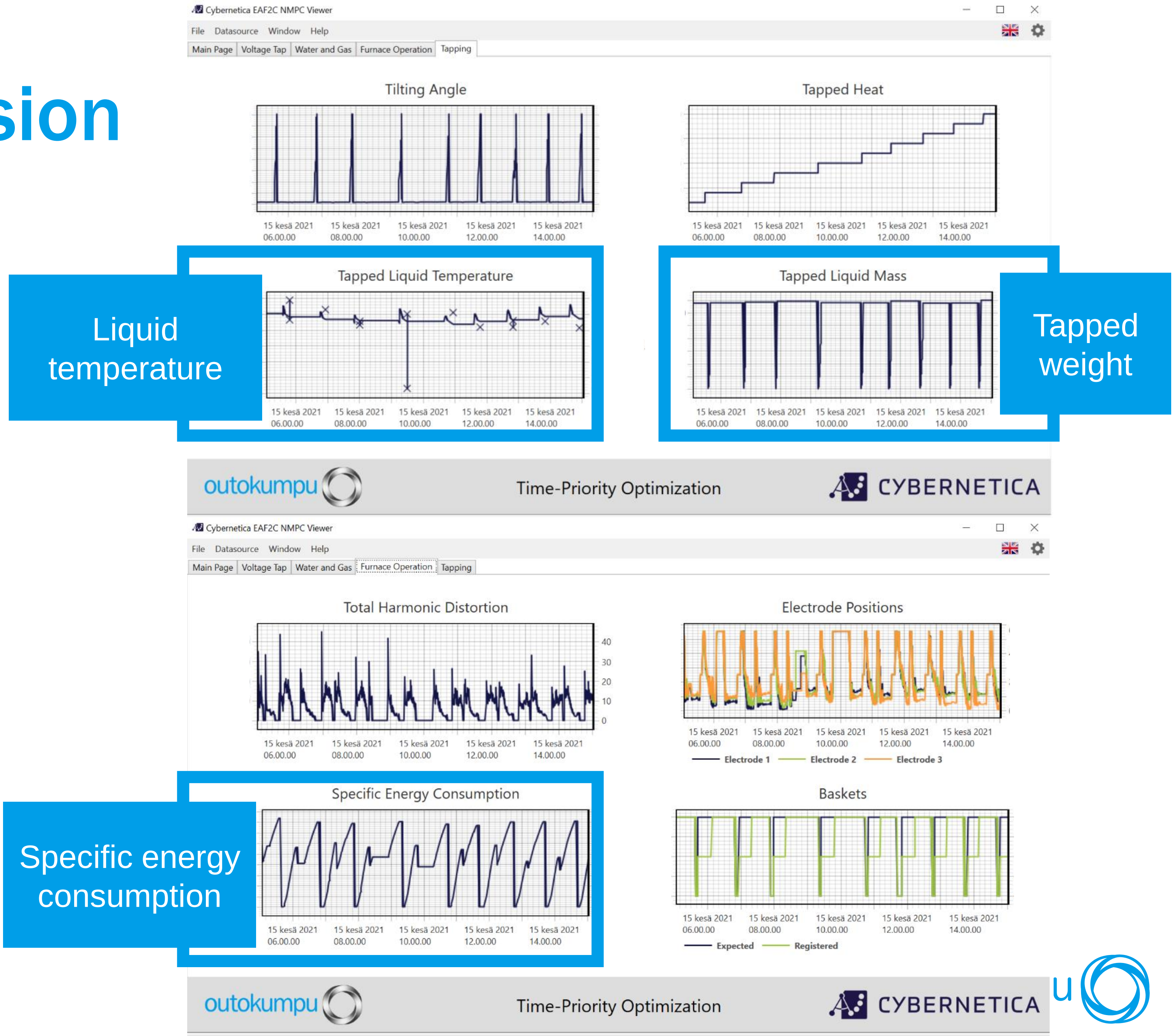
- The time-priority NMPC was applied for providing suggestions to the operators.
- The application also indicated when the scrap charge was fully melted.
- The operators executed the recommended voltage tap changes manually.
- The suggestions were found to be easy to follow in plant practice.



Results and discussion

Preliminary testing of the NMPC functionality

- The model also provides plenty of other information regarding the furnace operation.
- The predicted temperature of the metal is in reasonable agreement with the measured values.



Conclusions and outlook

- This work aimed to test the applicability of model predictive control for an industrial-scale EAF in stainless steelmaking.
- The results of the offline simulations were conducted for a 140-tonne EAF in operation at Outokumpu Stainless Oy in Tornio, Finland.
- The results indicate that the model can predict the final temperature and weight of the metal bath with good accuracy.
- The MPC application provides suggestions to the operator regarding optimized electrical power input.
- These suggestions were found to be easy to follow in plant practice.

Acknowledgements

- This work was executed within the framework of the Horizon 2020 SPIRE.
- The work was funded by the European Commission through the project Model-based optimization for efficient use of resources and energy (MORSE)

morse

spire2030.eu/morse

outokumpu

Special issue

Topic
Modeling and Simulation of Metallurgical Processes in Ironmaking and Steelmaking

Journal
Metals

Submission DL
July 15, 2021

The special issue is ideal for publishing research work on modelling the electric arc furnace.

Special Issue Editors

Dr. Thomas Echterhof Website
Guest Editor
Department for Industrial Furnaces and Heat Engineering, RWTH Aachen University, Kopernikustr. 10, 52074 Aachen, Germany
Interests: EAF steelmaking; industrial furnaces; process modelling and simulation; process analysis and optimization

Prof. Ko-Ichiro Ohno Website
Guest Editor
Department of Materials Science and Engineering, Faculty of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan
Interests: blast furnace; iron ore sintering; iron ore granulation; iron ore reduction reaction; self-reducing pellet; carbothermic reduction; cohesive zone; gasification behavior of carbonaceous materials; iron carburization behavior; iron ore softening and melting behavior; physical property of high temperature melts

Dr. Ville-Valtteri Visuri Website
Guest Editor
Process Metallurgy Research Unit, University of Oulu, PO Box 4300, 90014 Oulu, Finland
Interests: hot metal pretreatments; electric arc furnaces; converter metallurgy; ladle metallurgy; continuous casting; process modelling and simulation; kinetics and thermodynamics of metallurgical processes

Contact

Ville-Valtteri Visuri
Docent, D.Sc. (Tech.)
R&D Manager – Modeling
Research and Development

+358 50 412 5642
ville-valtteri.visuri@outokumpu.com

Outokumpu Stainless Oy
Terästie, FI–95490 Tornio

Thank you for your attention!

outokumpu