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# On the importance of heat exchange modelling assumptions in electric arc furnace process models

**Acciai Speciali Terni Spa.**

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# Outlook of this presentation

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- Introduction
- Modelling of the EAF
  - Importance of assumptions in heat exchange modeling
  - On the predictions and the results of the optimizer
- Results of a successful case study
- Conclusions

# 1/5 Introduction



# Pronto objective

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**WHAT:** Optimize the electrical energy performance of the process

**WHY:** To improve the economics and the environmental performance of the EAF process. **i.e.** A reduction of 3% in the electrical energy of our process will offset around 12 to 18 KTon<sub>eq</sub> CO<sub>2</sub>/year and have equal economic improvements

**HOW:** Using a Dynamic Optimization framework that maximizes the energy efficiency of the EAF by setting optimal set-points to the process (Electrical, chemical, ...).

# Introduction

## Dynamic Optimization

Open Loop Optimal Control

Off-line NMPC

max. Electrical Energy Efficiency  $\eta(v,z)$

Subject to: **Dynamic system:** evolution of mass and temperature of the solid and liquid metal.

**Algebraic system:** Energy heat transfer mechanisms from the arc, the burners, and others, relation between voltage, impedance arc length

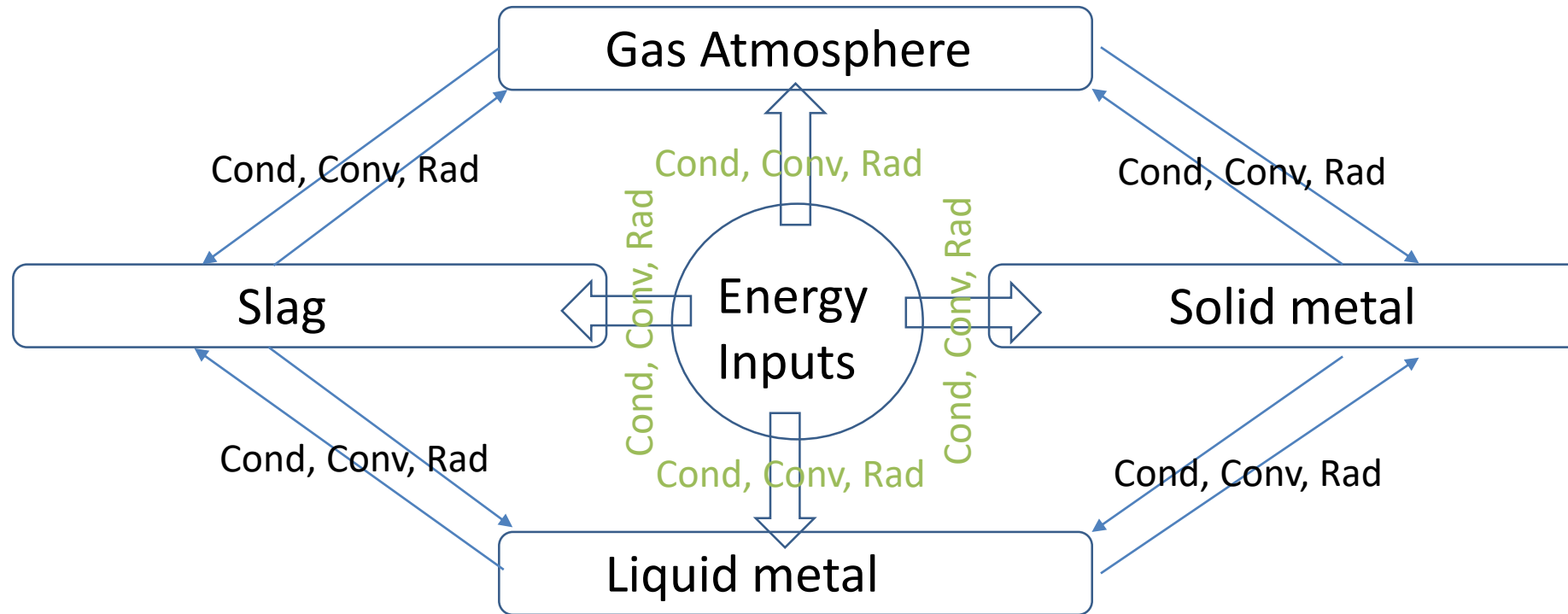
**Terminal constraints:** temperature of the melt.

**2/5**  
**EAF Model**



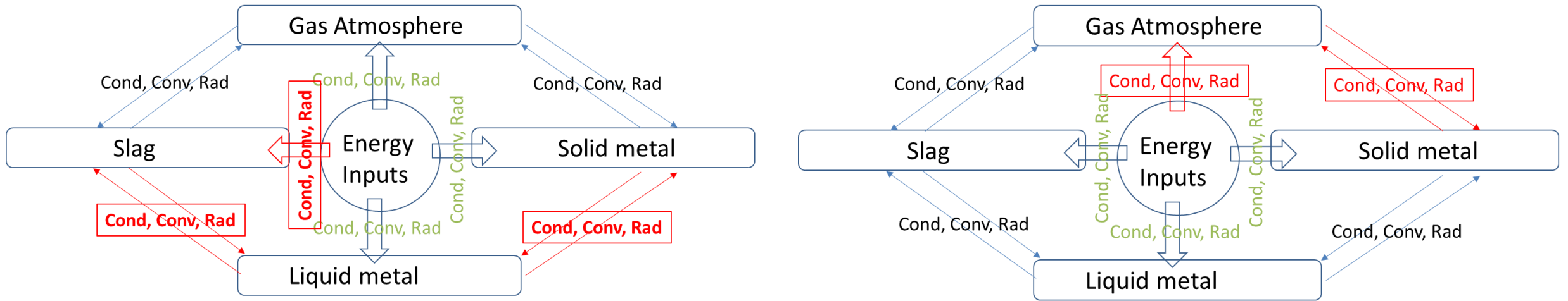
# Importance of assumptions in heat exchange modeling

The melting dynamics are mostly determined by the heat exchanges



We make many assumptions regarding all these, the paths of flow of energy and values of heat transfer constants

# Importance of assumptions in heat exchange modeling



The energy demand of the process can be satisfied assuming different energy flow paths, and tweaking the heat constants as needed! (either assuming or using parameters estimation frameworks).

**The problem is: different energy paths determine difference melting dynamics, thus different optimal control strategies!!**

**Most Importantly -> Certain modeling assumptions may lead to a non-controlable system!**



# Importance of assumptions in heat exchange modeling

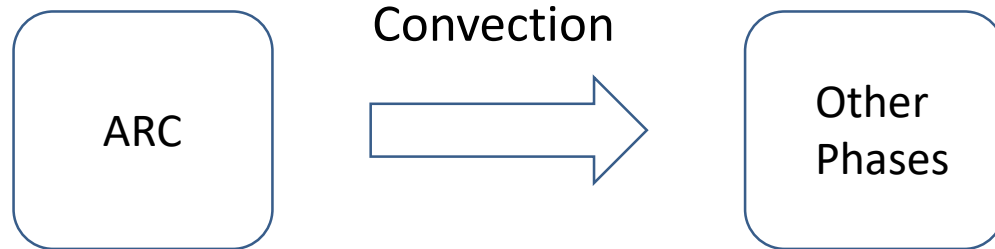
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Controlability in linear systems -> Check controlability matrix

Controlability in non-linear systems (EAF) -> Might be computed locally. However, one can provide an educated guess by checking the **causality** between inputs and outputs

# Importance of assumptions in heat exchange modeling

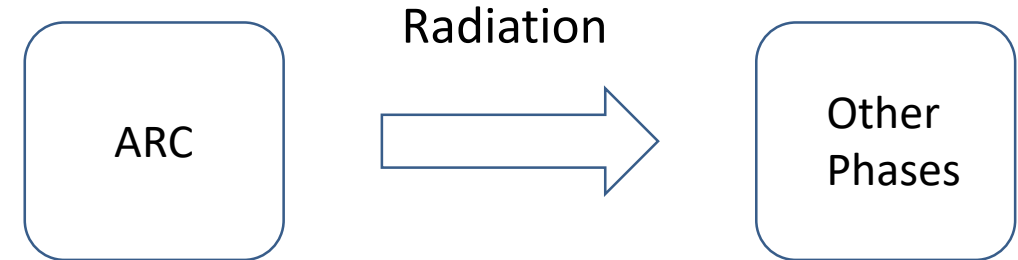
## Causality



Heat must be removed by air flow

Causality between input and output:

- An electrical current creates a flow of air around the plasma columns due to Maecker's effect
- Is small and restricted



Heat does not need any media to be transported

Causality between input and output:

- Voltage/Impedance setpoints determine the arc geometry, which in turn determines the radiative energy fluxes in the system
- Any amount of heat can be removed by radiation

# The EAF model

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The developed model was built with the ambition to address some still open questions:

- What are the dominant mechanisms of heat transfer?
- What is the best modelling geometry?
- Can heat transfer coefficients be assumed constant through the batch, how does this assumption impact the dynamics of the process?
- What is the effect of the electrical setpoints in the efficiency of the process (how various voltage/impedance setpoints affect the heat exchange in the interior of the EAF)?

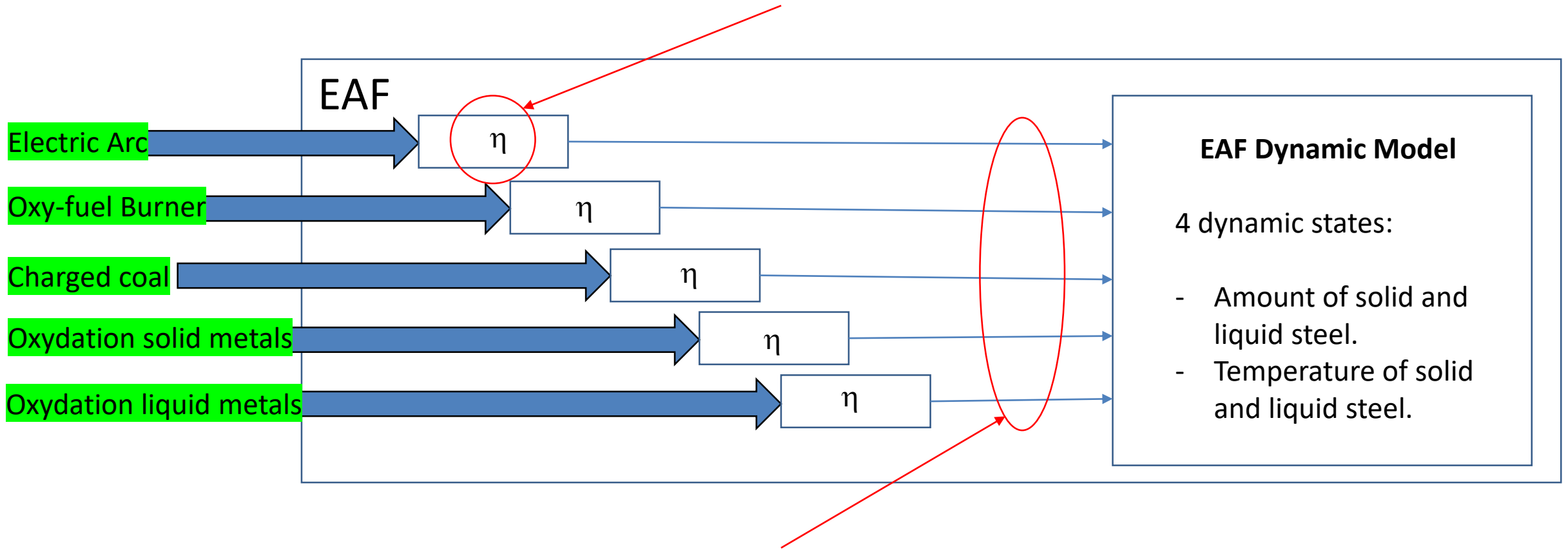
# The EAF model

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- Describes the operation of an EAF operating mostly with scrap
- Lancing practices start late in the batch
- A very thin slag layer is considered
- Radiation is the only mechanisms of heat exchange from the arc to the rest of the phases[1][2]
- Uses the hollowed cylinder geometry – suggested by operators!!!
- Employ a burner model which efficiency varies with scrap density, charging practices, and flow rates of gases [3]
- The oxydation of solid metals is restricted to physical phenomena - corrosion laws
- Includes an arc model that transforms voltage impedance setpoints into arc lenghts and operational powers [4]

# Importance of assumption in heat exchange modeling

Given by: first principles and empirical relationships (might help to reduce the need for tweaking while imposing limits to the energy contribution of each source)

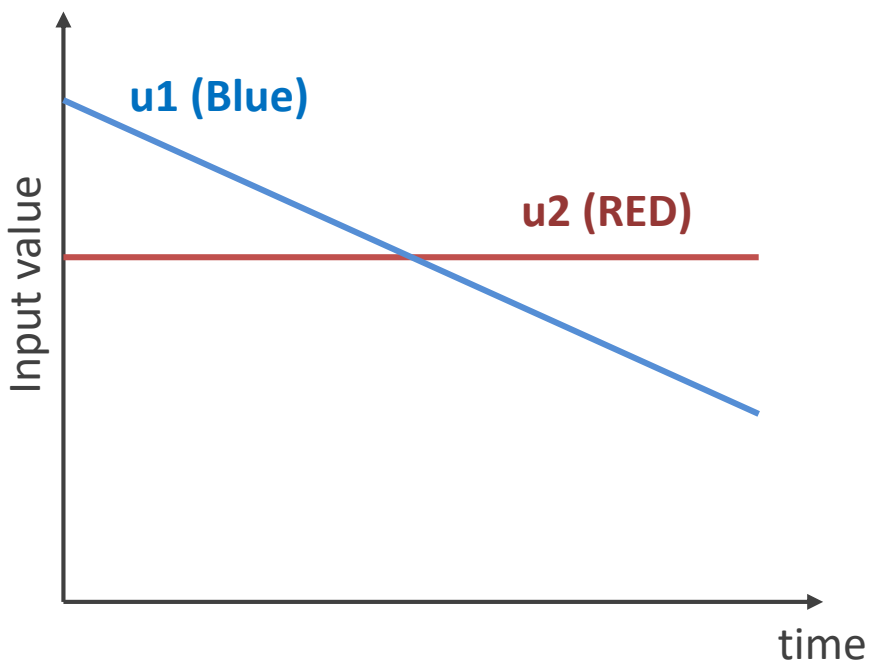


Helps to clarify what energy streams occur when and how much do they contribute to the process

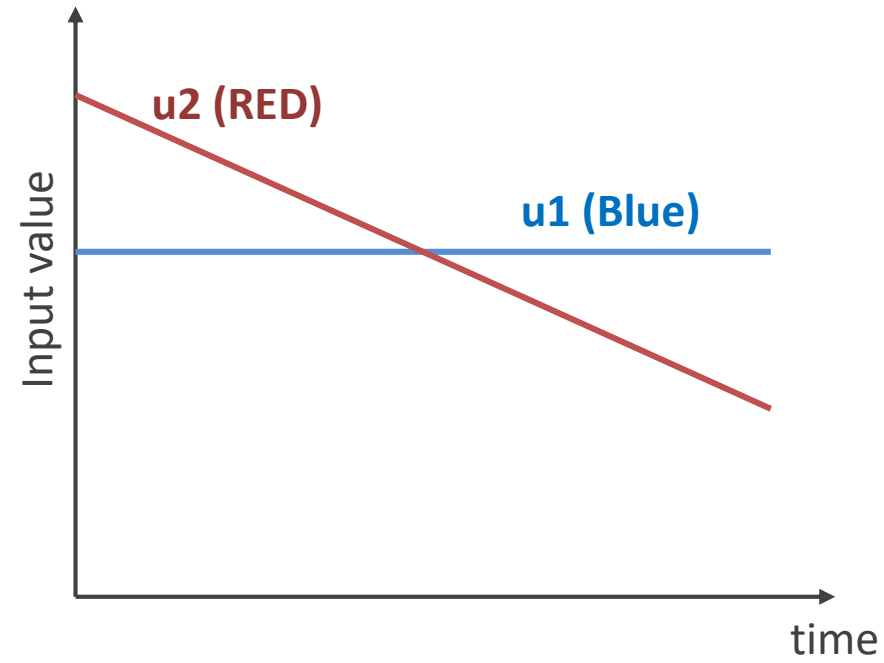
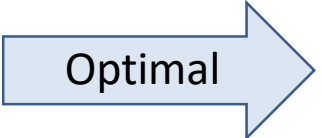
# 3/5 Results



# Results of the optimization

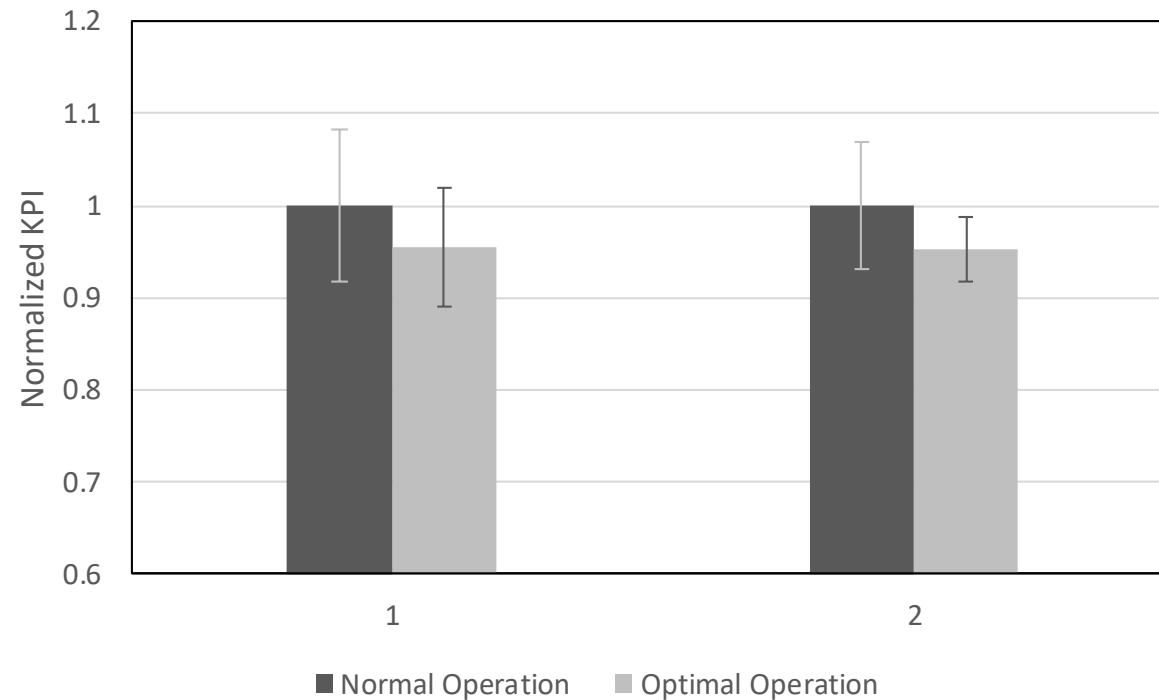


Standard operation



Optimal operation

# Results of the optimization



Operation improvements regarding 1. batch time and 2. energy demand of the process for 19 test batches

[5] J. D. Hernandez, L. Onofri and S. Engell, "Optimization of the electric efficiency of the electric steel making process", in 21st IFAC World Congress, Berlin, Germany, 2020



# 4/4 Conclusions



# Conclusions

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- Different modeling assumptions lead to different paths of evolution of the process. Locally many paths could be feasible as the terminal/validation state can be achieved in various ways. This is done by tweaking / estimating the heat constant parameters as required. Multiplicity of paths is a big problem in optimization.
- For optimization/control applications, one needs to check that a realistic causal relationship between the controlled variable and the manipulated variable exists. Every assumption determines a path of evolution to the process. If the assumptions employed do not match well the reality of the process, the optimizer will provide pseudo-optimal operational points that lie far away from the true optimal of the plant.
- Restricting the domain of the adjusted variables can help to identify what modeling assumptions are wrong (terminal states could not be reached for certain values of the estimated parameters).

# Conclusions

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- Because:
  1. operational experience suggest that the efficiency of the melting process can be influenced by changing the operative setpoints of the electric arc
  2. The effect of the electrical setpoints on the melting process is better explained by radiation than convection,
  3. A large amount of work in the plasma research literature suggests that radiation is the dominant mechanism of heat loss in the arc [6]
  4. The assumption of a radiation dominated process led to the discovery of a melting profile that improved mode of operation of the EAF (energy wise) – this prediction was later validated in a real UHP-EAF,

We conjecture that the EAF process with thin slag layers is radiation dominated.

# Bibliography

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6. J. J. Lowke, "Characteristics of radiation-dominated electric arcs," *J. Appl. Phys.*, vol. 41, pp. 2588-2600, 1970.

# Acknowledgements

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